ANALYSIS OF POSSIBLE EXPLOSION AT KSC DUE TO SPONTANEOUS IGNITION OF HYPERGOLIC PROPELLANTS

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1.0 INTRODUCTION

NASA's Constellation Program plan currently calls for the replacement of the Space Shuttle with the ARES I & V spacecraft and booster vehicles to send astronauts to the moon and beyond. Part of the ARES spacecraft is the Orion Crew Exploration Vehicle (CEV), which includes the Crew Module (CM) and Service Module (SM). The Orion CM's main propulsion system and supplies are provided by the SM. The SM is to be processed off line and moved to the Vehicle Assembly Building (VAB) for stacking to the first stage booster motors prior to ARES move to the launch pad. The new Constellation Program philosophy to process in this manner has created a major task for the KSC infrastructure in that conventional QD calculations are no longer viable because of the location of surrounding facilities near the VAB and the Multi Purpose Processing Facility (MPPF), where the SM will be serviced with nearly 18,000 pounds of hypergolic propellants.

Engineering Analysis Inc. (EAI), under contract with ASRC Aerospace, Inc. in conjunction with the Explosive Safety Office, NASA, Kennedy Space Center (KSC), has carried out an analysis of the effects of explosions at KSC in or near various facilities produced by the spontaneous ignition of hypergolic fuel stored in the CEV SM. The facilities considered included

- Vehicle Assembly Building (VAB)
- Multi-Payload Processing Facility (MPPF)
- Canister Rotation Facility (CRF)

Subsequent discussion deals with the MPPF analysis. The MPPF complex, constructed by NASA in 1994, is located just off E Avenue south of the Operations and Checkout (O&C) building in the Kennedy Space Center industrial area. The MPPF includes a high bay and a low bay. The MPPF high bay is 40.2 m (132 ft) long x 18.9 m (60 ft) wide with a ceiling height of 18.9 m (62 ft). The low bay is a 10.4 m (34 ft) long x 10.4 m (34 ft) wide processing area and has a ceiling height of 6.1 m (20 ft). The MPPF is currently used to process non-hazardous payloads. Figure 1 provides a view of the MPPF from the northwest. An interior view of the facility is shown in Figure 2.

The study was concerned with both blast hazards and hazardous fragments which exceed existing safety standards, as described in Section 2.0. The analysis included both blast and fragmentation effects and was divided into three parts as follows:

- blast
- primary fragmentation
- secondary fragmentation

Blast effects are summarized in Section 3.0, primary fragmentation in Section 4.0, and secondary fragmentation (internal and external) in Section 5.0. Conclusions are provided in Section 6.0, while references cited are included in Section 7.0. A more detailed description of the entire study is available in a separate document [1]. The study conformed to certain guidelines specified by NASA/KSC [2].

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* Numbers in brackets refer to references cited as presented in Section 7.0.

Figure 1. Multi-Payload Processing Facility (MPPF)

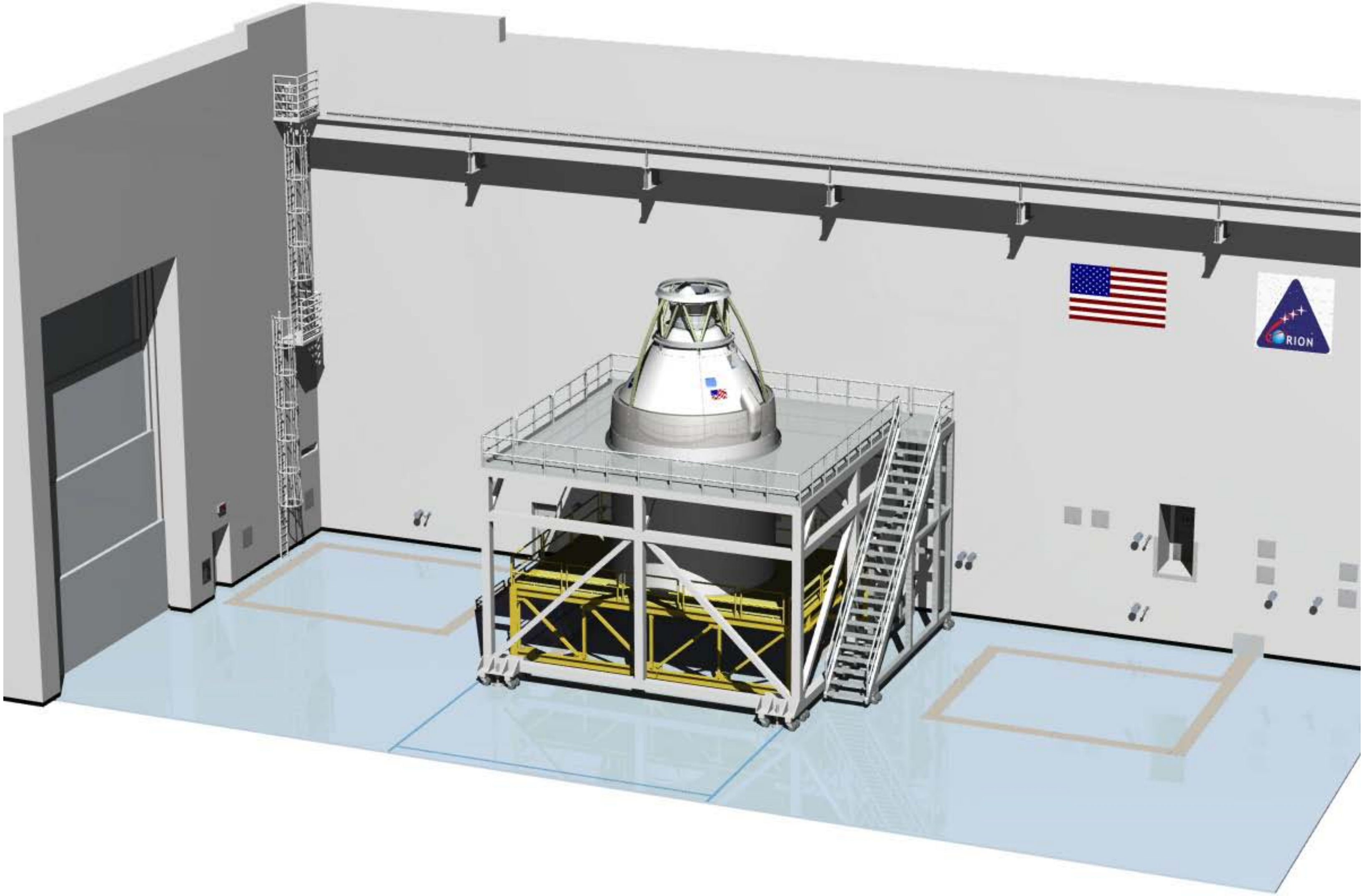

Figure 2. CEV 606 Short Stack Surrounded By Access Stand Positioned Within MPPF Highbay

2.0 SAFETY STANDARDS

Relevant safety standards [3 - 6] specify overpressure limits for inhabited buildings from 0.9 to 1.2 psi. Likewise, for fragmentation hazards, fragment impact energies in excess of 58 ft-lb_f, in number densities greater than 1 per 600 square feet, (as measured in a vertical plane one foot wide extending from ground level up to an elevation of 6 feet) are considered hazardous. For a building containing explosives with a TNT equivalence on the order of 1000 lb_m, the inhabited building distance is 1250 feet from the perimeter of the building. Figure 3 provides a plan view of the explosive safety arc and nearby KSC structures.

3.0 BLAST EFFECTS

The hypergolic fuel contained within the CEV Service Module with a total mass (including 20% design growth margin) of 21,591 lbs, was assumed to detonate with an equivalent yield of 1080 lbs of TNT. The CEV was positioned in the Access Stand within the MPPF high bay, as shown in Figure 4. All relevant components of the MPPF, both internal and external, were included in the analysis, along with all significant surrounding structures within a range of 1250 feet, or slightly further, from the MPPF. Blast effects were computed by means of the HEXDAM software [7]. Five views of the undamaged MPPF structure, as generated by HEXDAM, are presented in Figures 5 through 9. The corresponding five views of the MPPF with blast damage are presented in Figures 10 through 15. As indicated in these last five figures, severe blast damage was predicted to much of the roof, as well as all four faces of the MPPF.

With regard to overpressure predictions, both 0.9 and 1.2 psi horizontal contour plots were generated at eight different elevations, ranging from 0 to 70 feet. The maximum ranges for such contours occurred at 50 feet, as shown in Figure 16. As indicated in this figure, the 1.2 psi overpressure contour extended out no more than 355 feet from the MPPF perimeter while the 0.9 psi overpressure contour extended out no more than 436 feet. The results indicated significant hazard to the MPPF itself but no significant hazards to the surrounding buildings would result from blast effects. A summary of blast hazards is provided in Table 1.

Table 1. Summary of MPPF Blast Hazards

FACILITY #/NAME	HAZARDS
M7-1104/MPPF High Bay	Moderate-to-Severe
M7-1104/MPPF North Office	None-to-Severe
M7-1104/MPPF Low Bay	None-to-Severe
M7-1104/MPPF Flight Data Control Room	Slight-to-Severe
M7-1104/MPPF Annex	None-to-Severe
M7-1357/Multi Operations Support Bldg (MOSB)	None-to-Slight
M7-1354/Payload Hazardous Servicing Facility (PHSF) Bldg	None-to-Slight
M7-1355/PHSF Storage Bay	None-to-Slight
M7-1059/Hypergolic Maintenance Facility	None-to-Slight
M7-0777/Canister Rotation Facility - High Bay	None-to-Slight
M7-0777/Canister Rotation Facility - Office Area	None

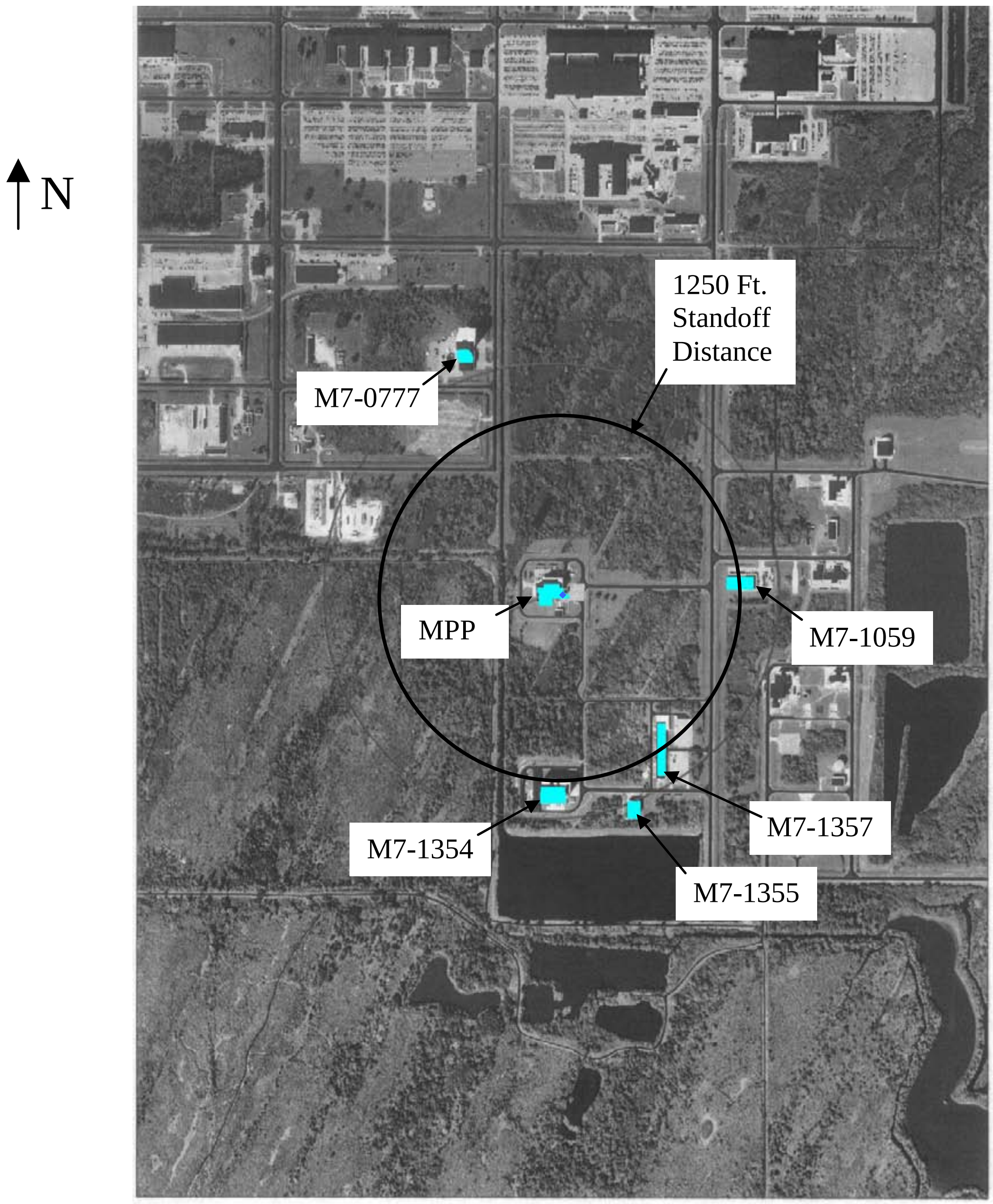

Figure 3. KSC Buildings in Vicinity of MPPF

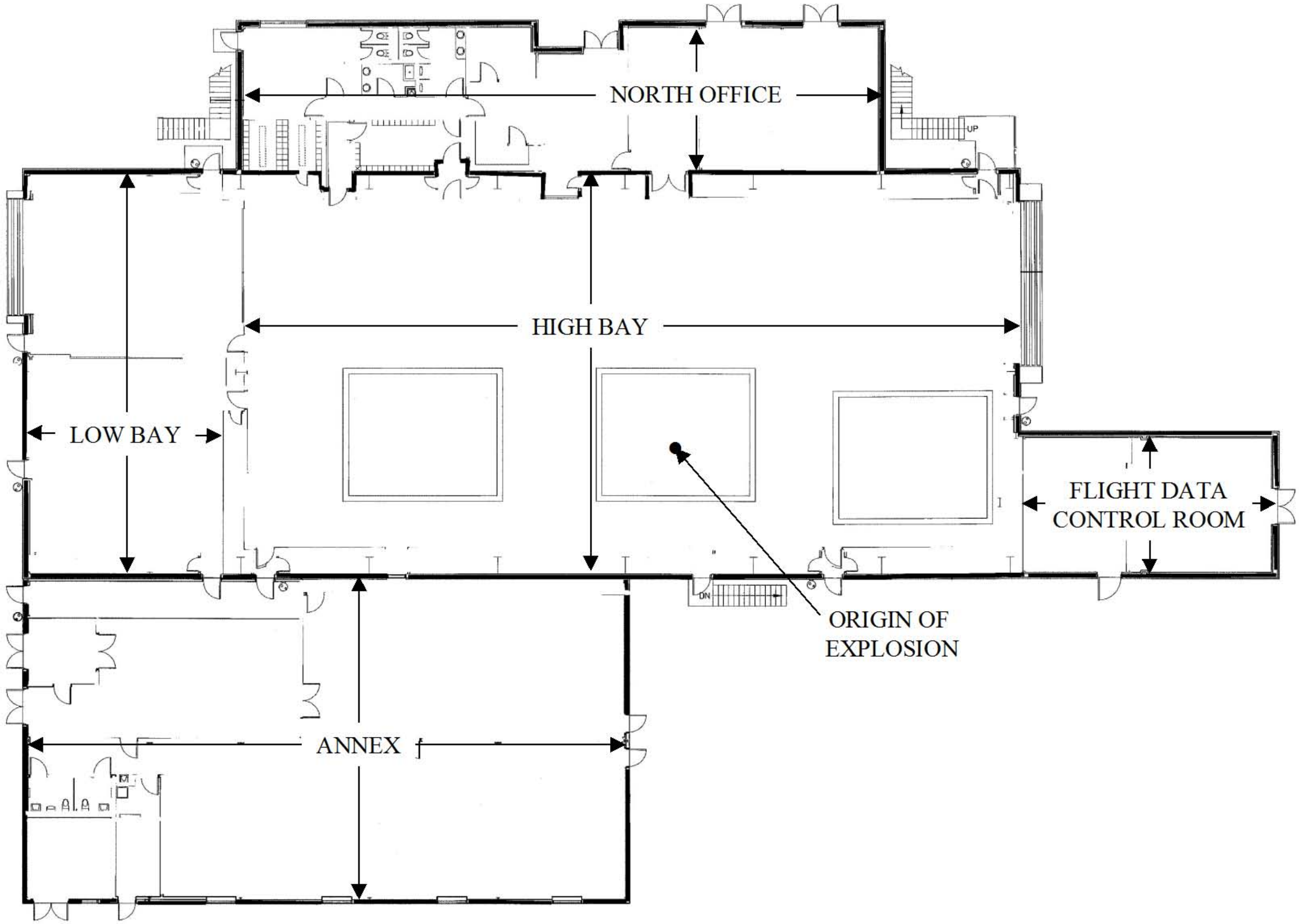

Figure 4. MPPF Plan View

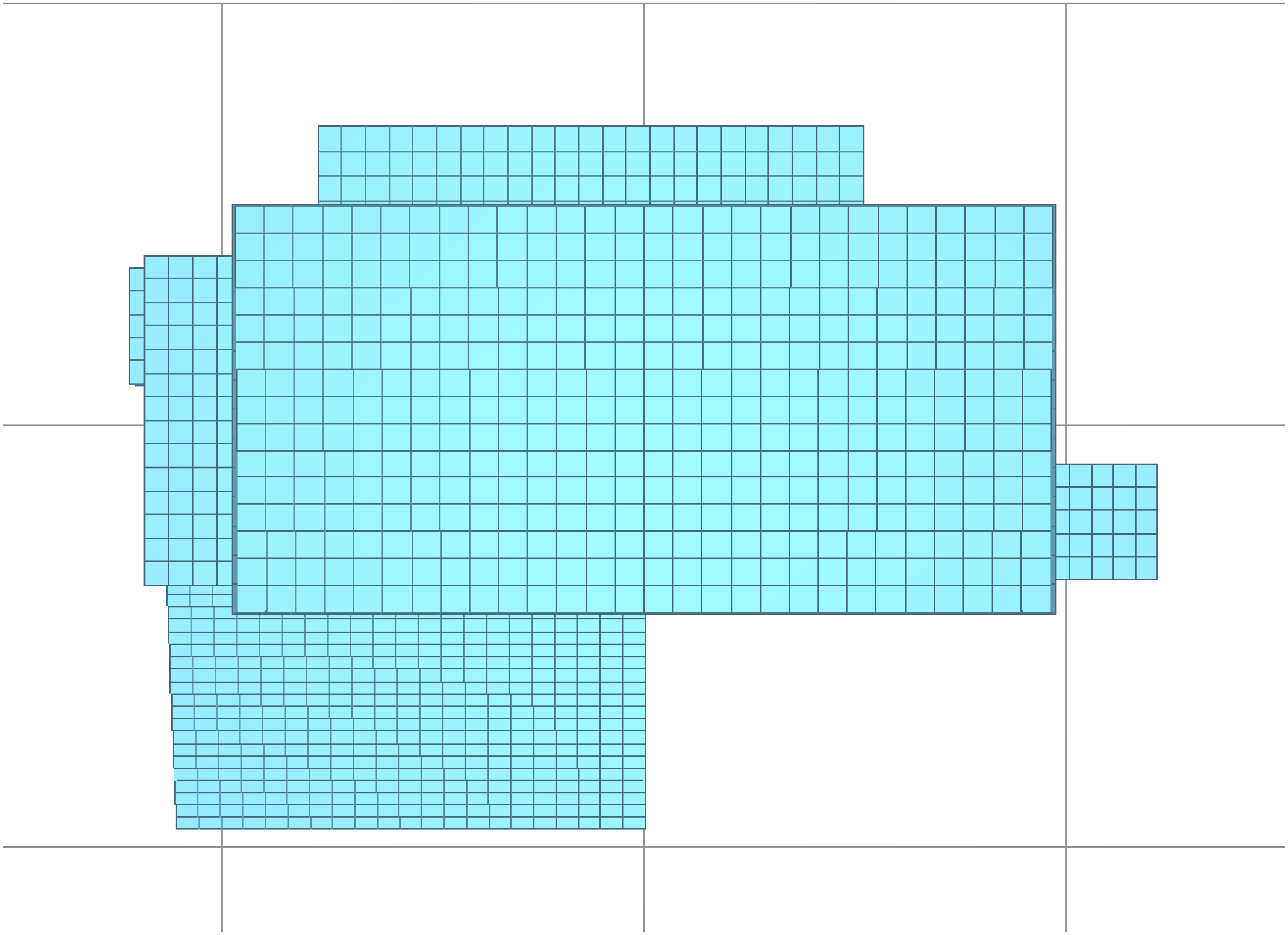

Figure 5. MPPF Roof

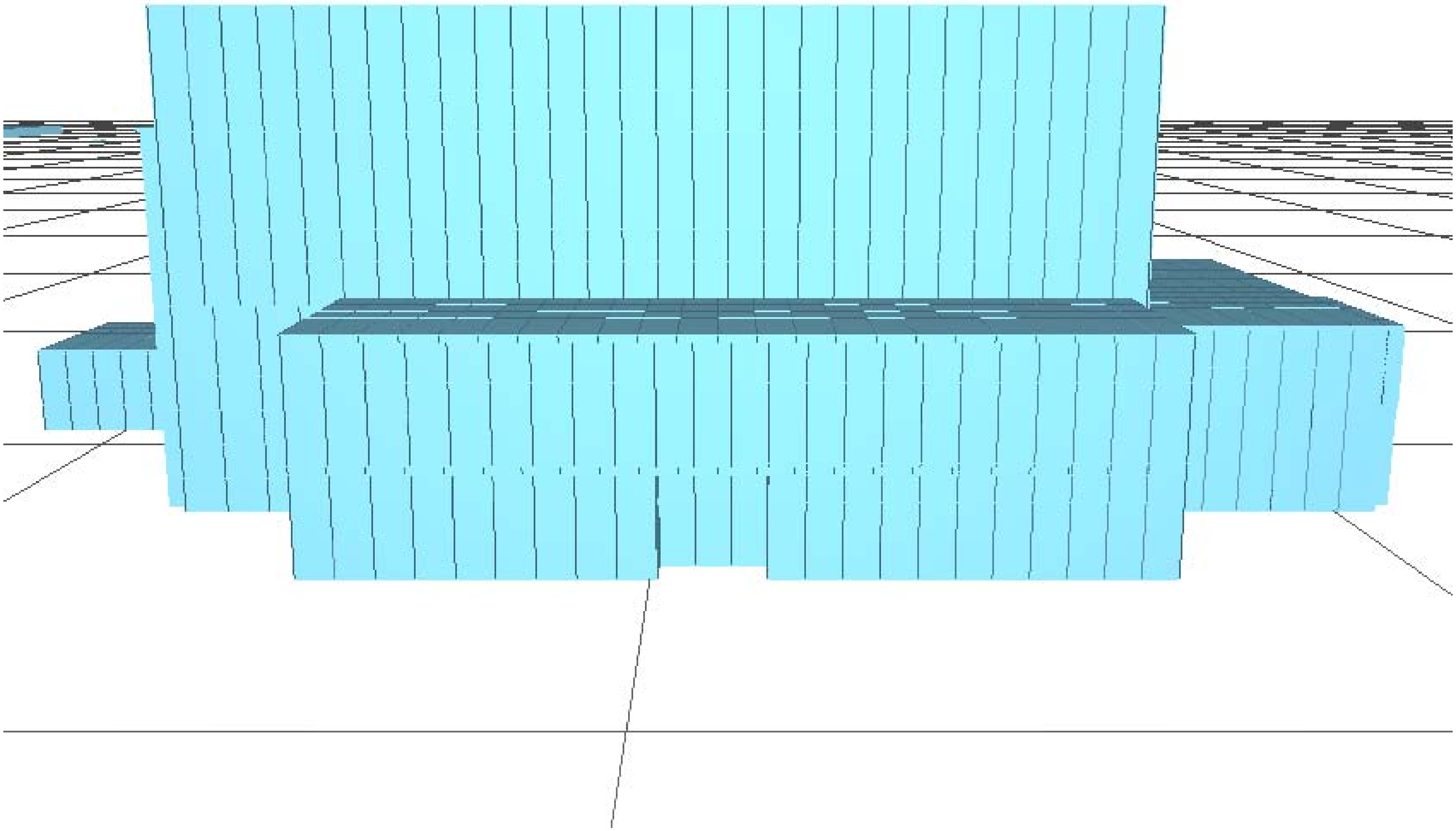

Figure 6. MPPF North Face

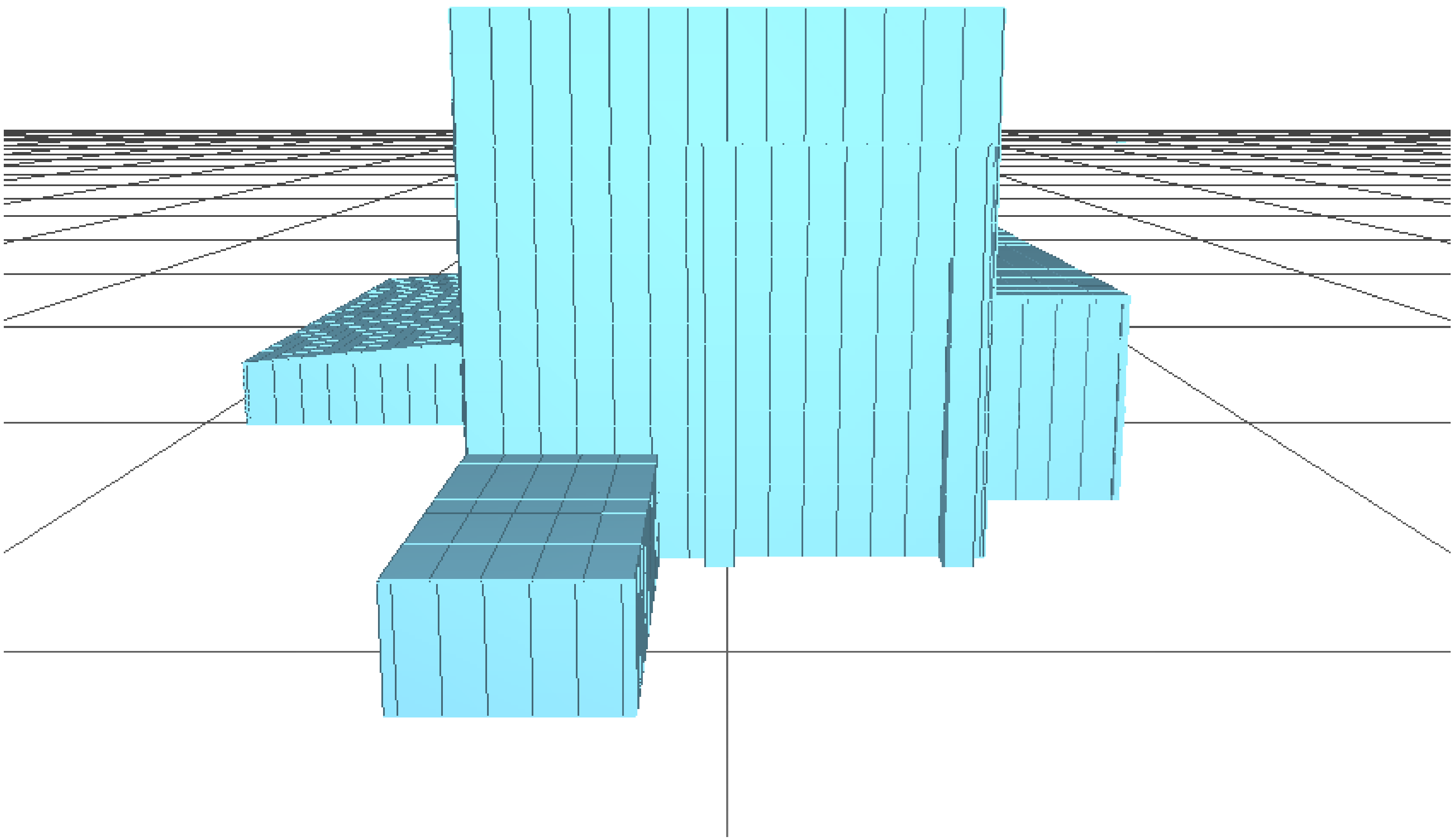

Figure 7. MPPF East Face

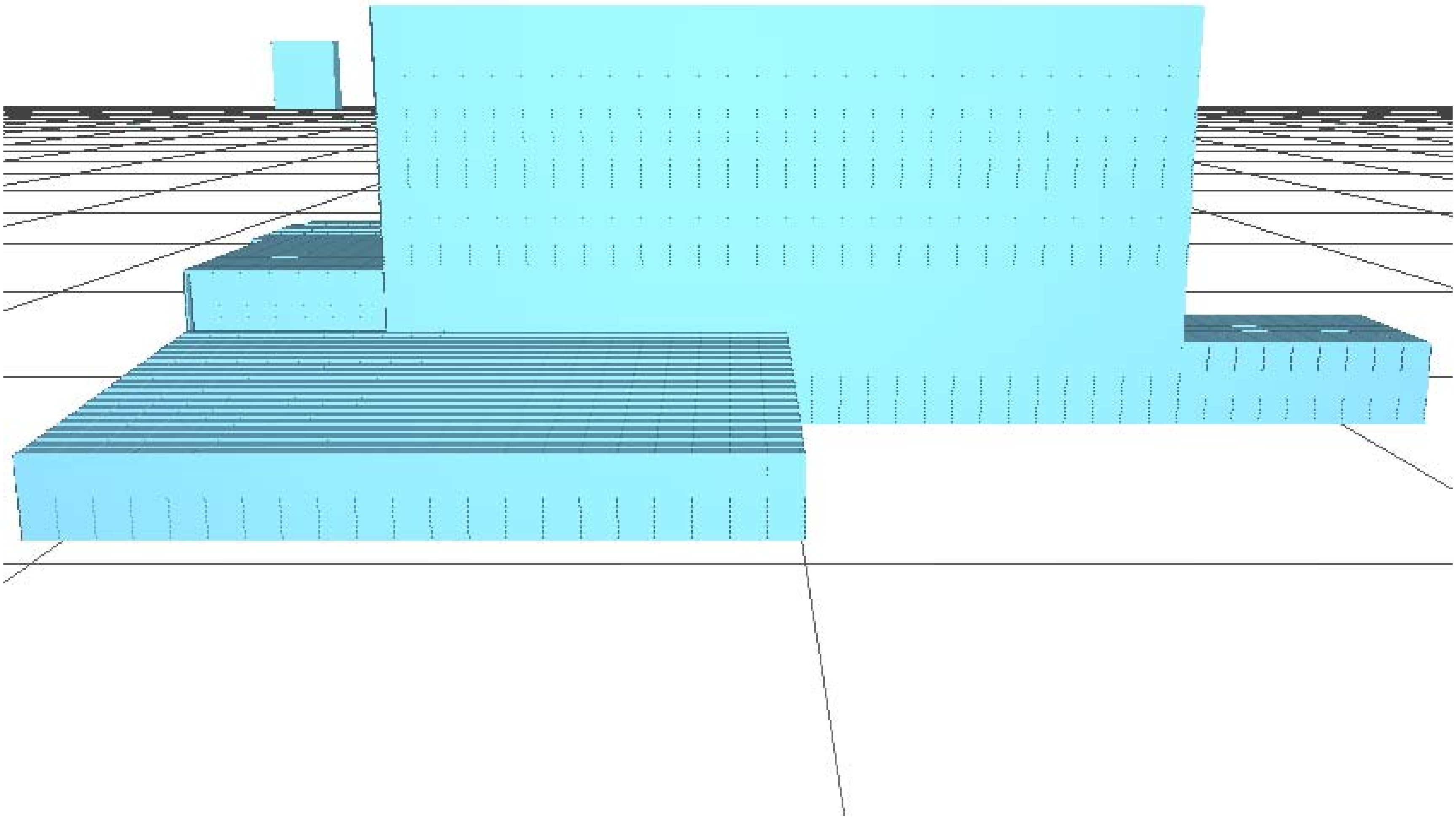

Figure 8. MPPF South Face

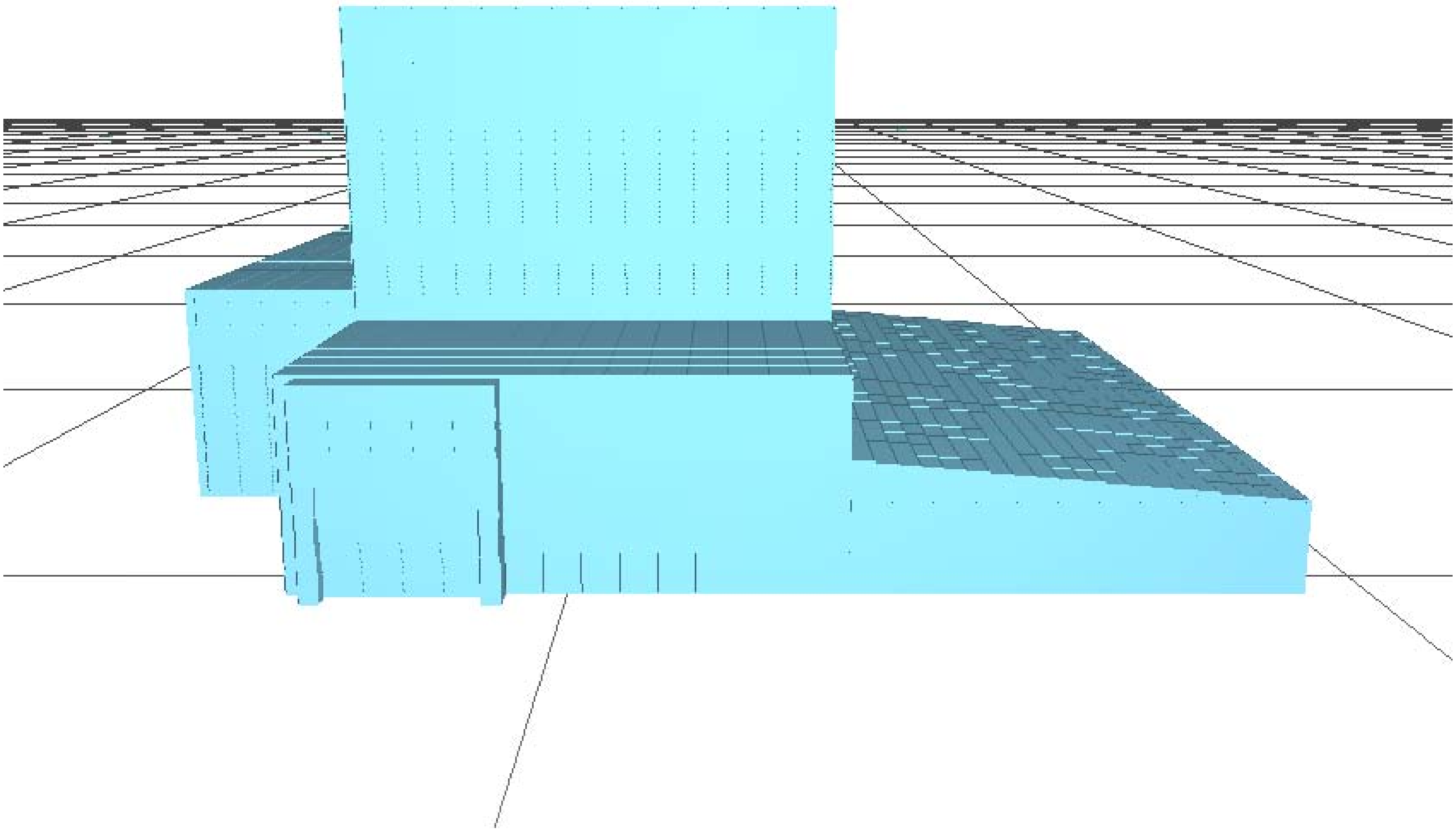

Figure 9. MPPF West Face

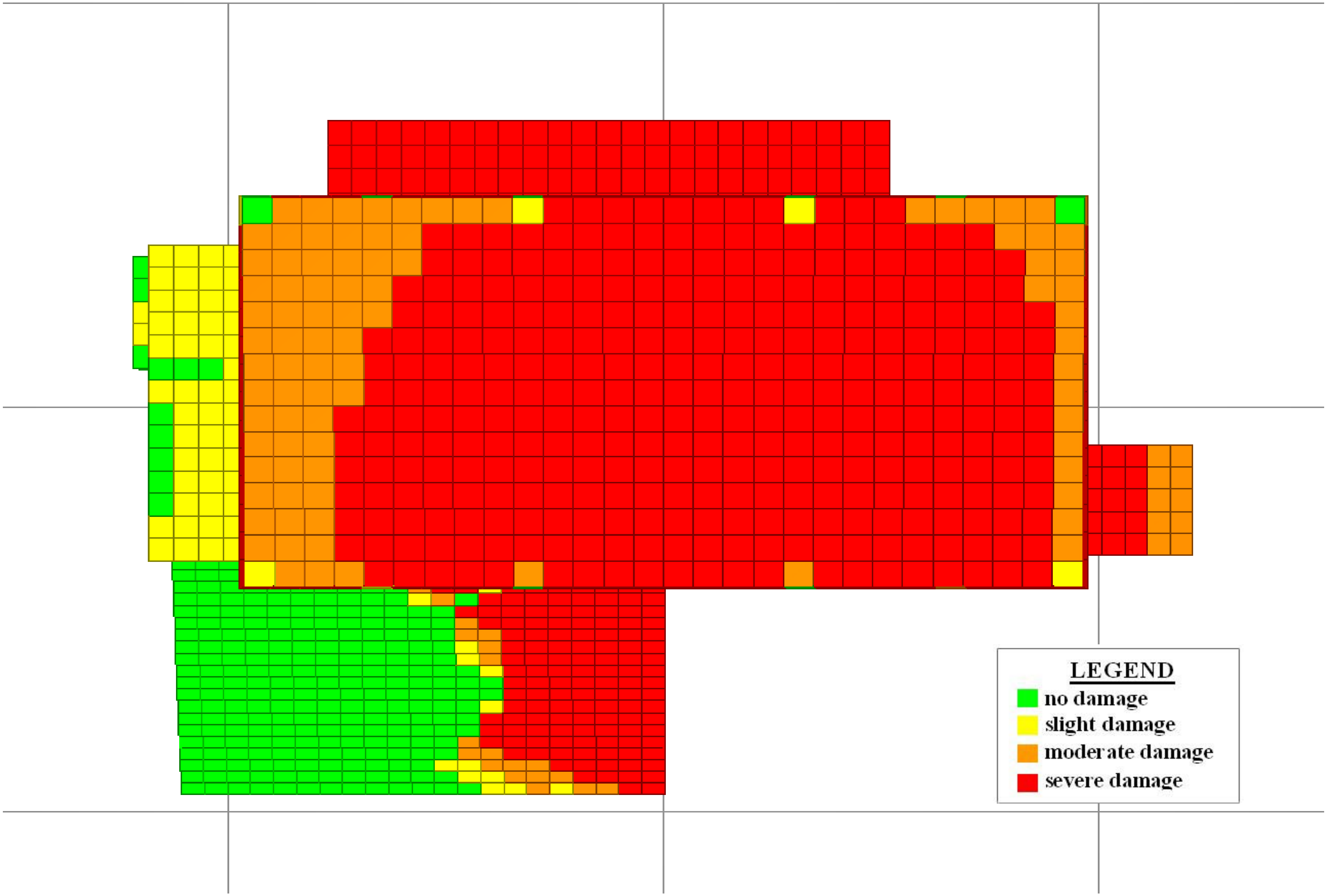

Figure 10. Damage Plot, MPPF Roof

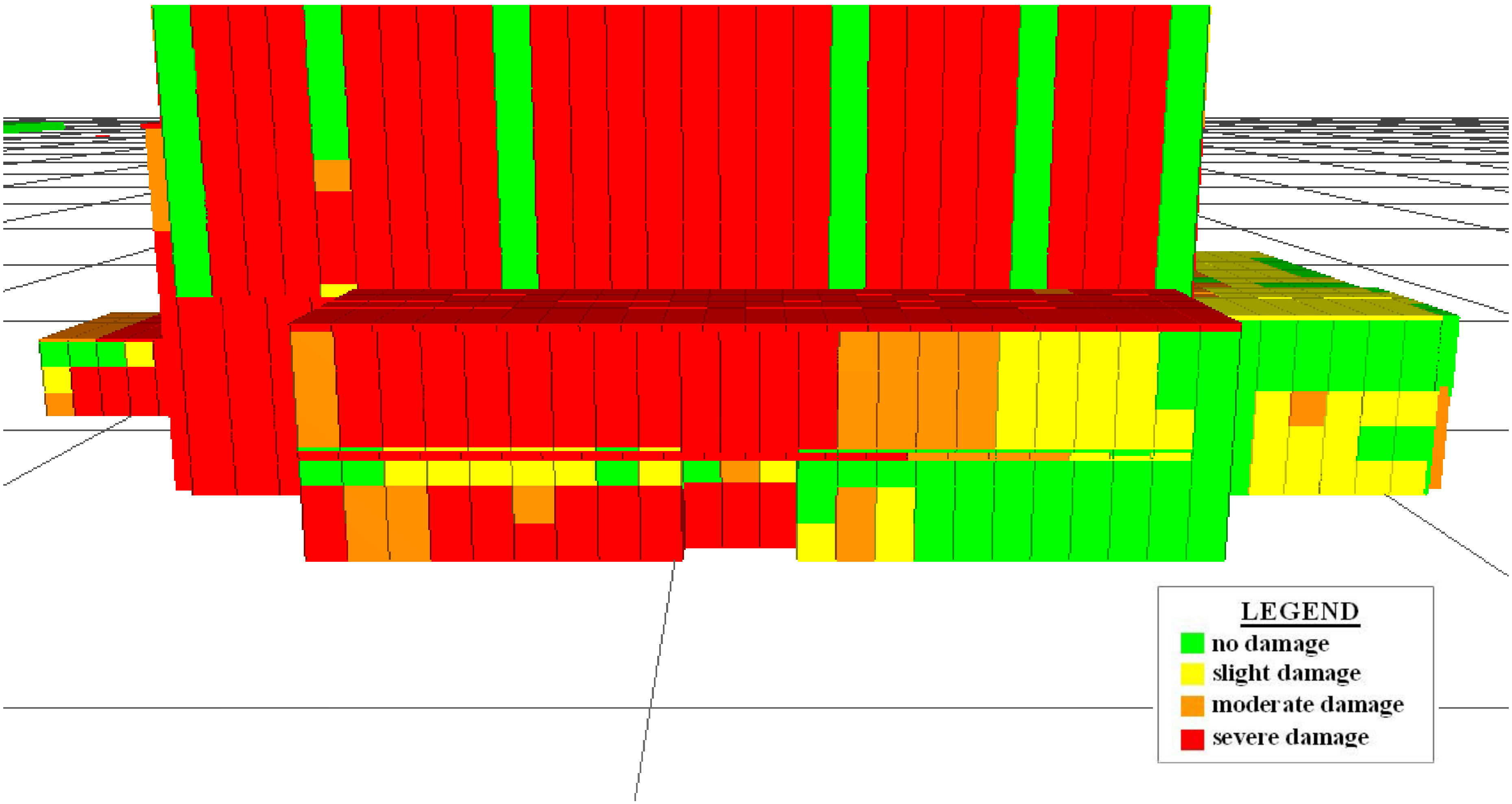

Figure 11. Damage Plot, MPPF North Face

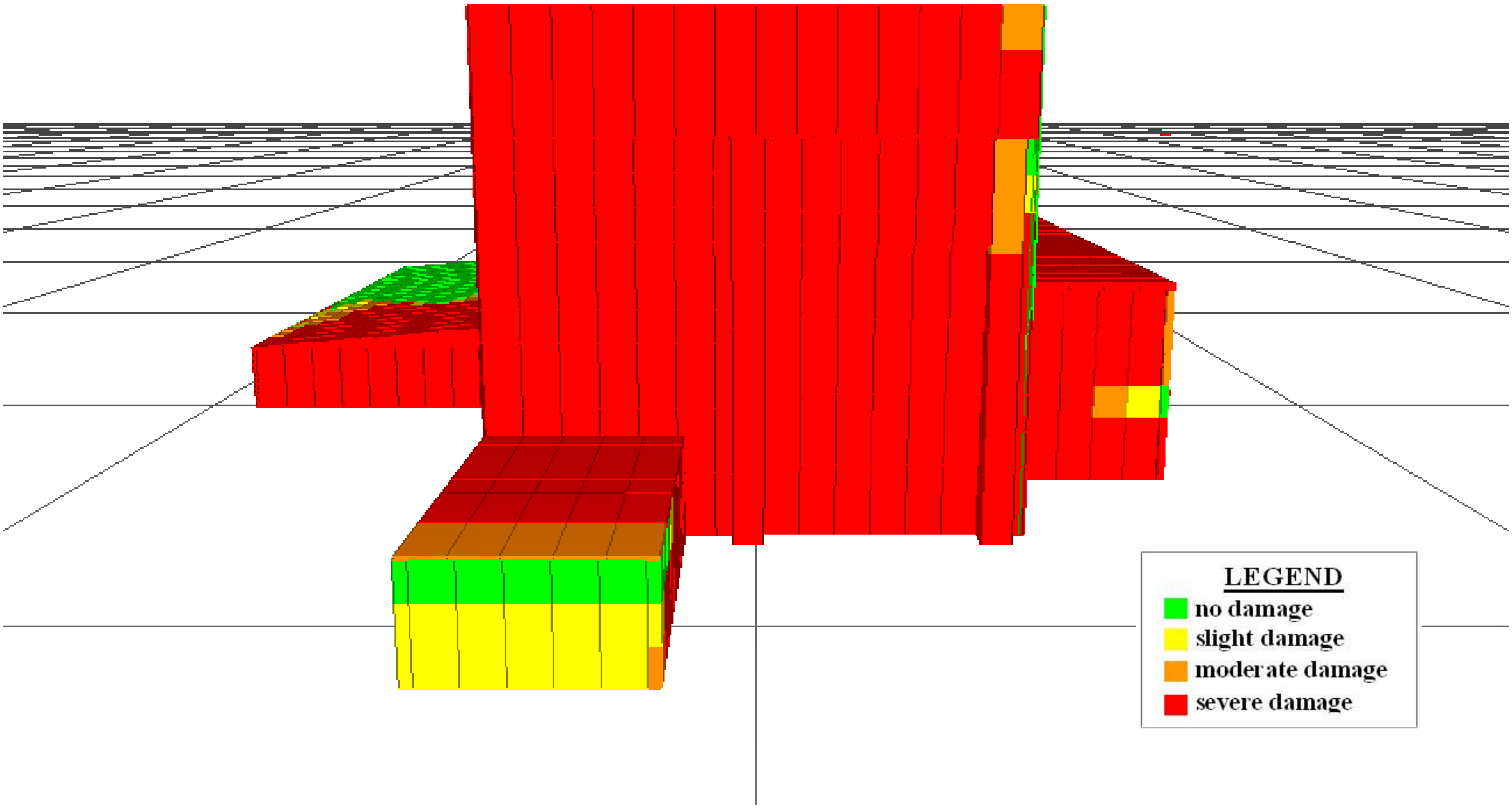

Figure 12. Damage Plot, MPPF East Face

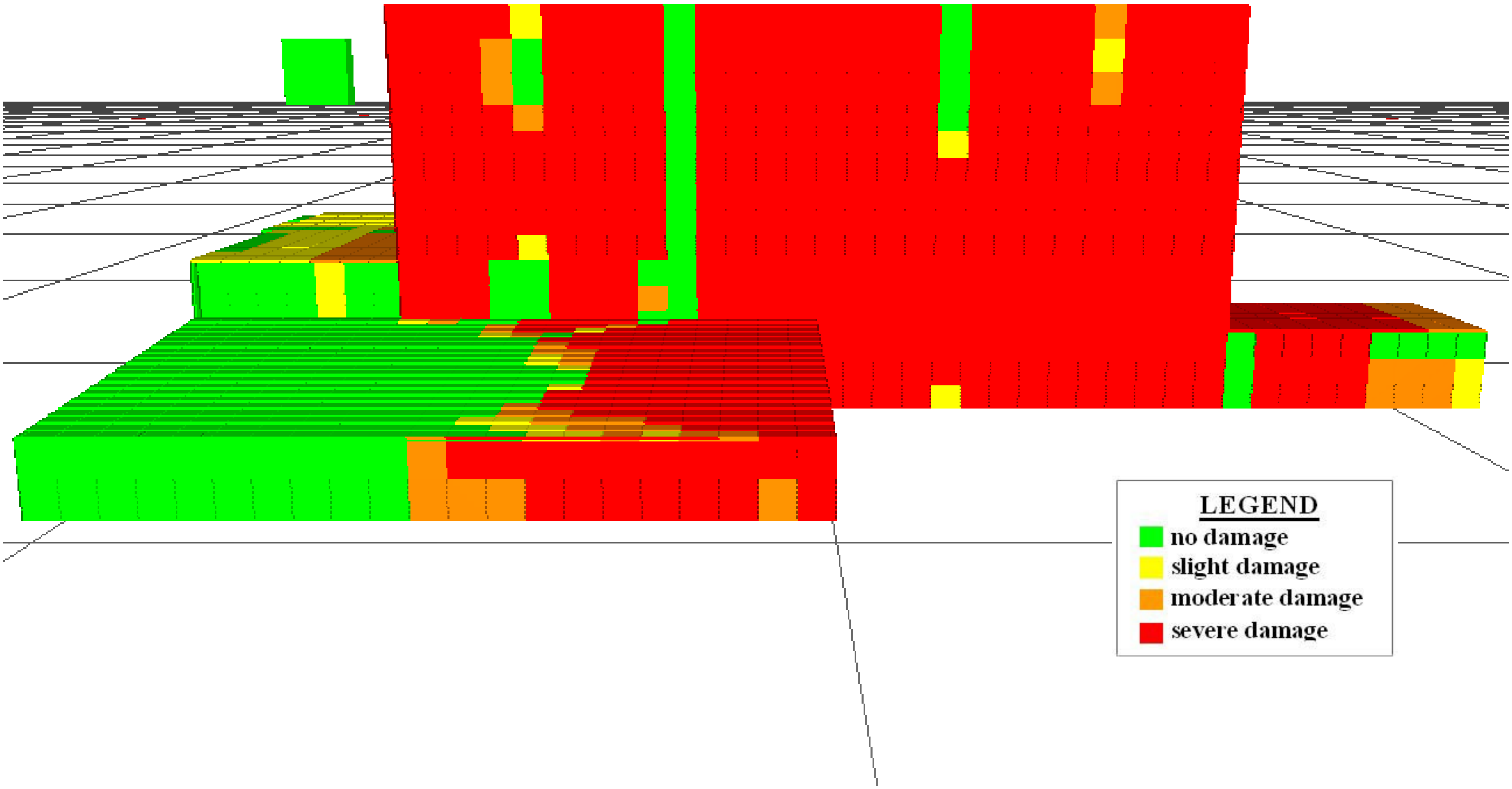

Figure 13. Damage Plot, MPPF South Face

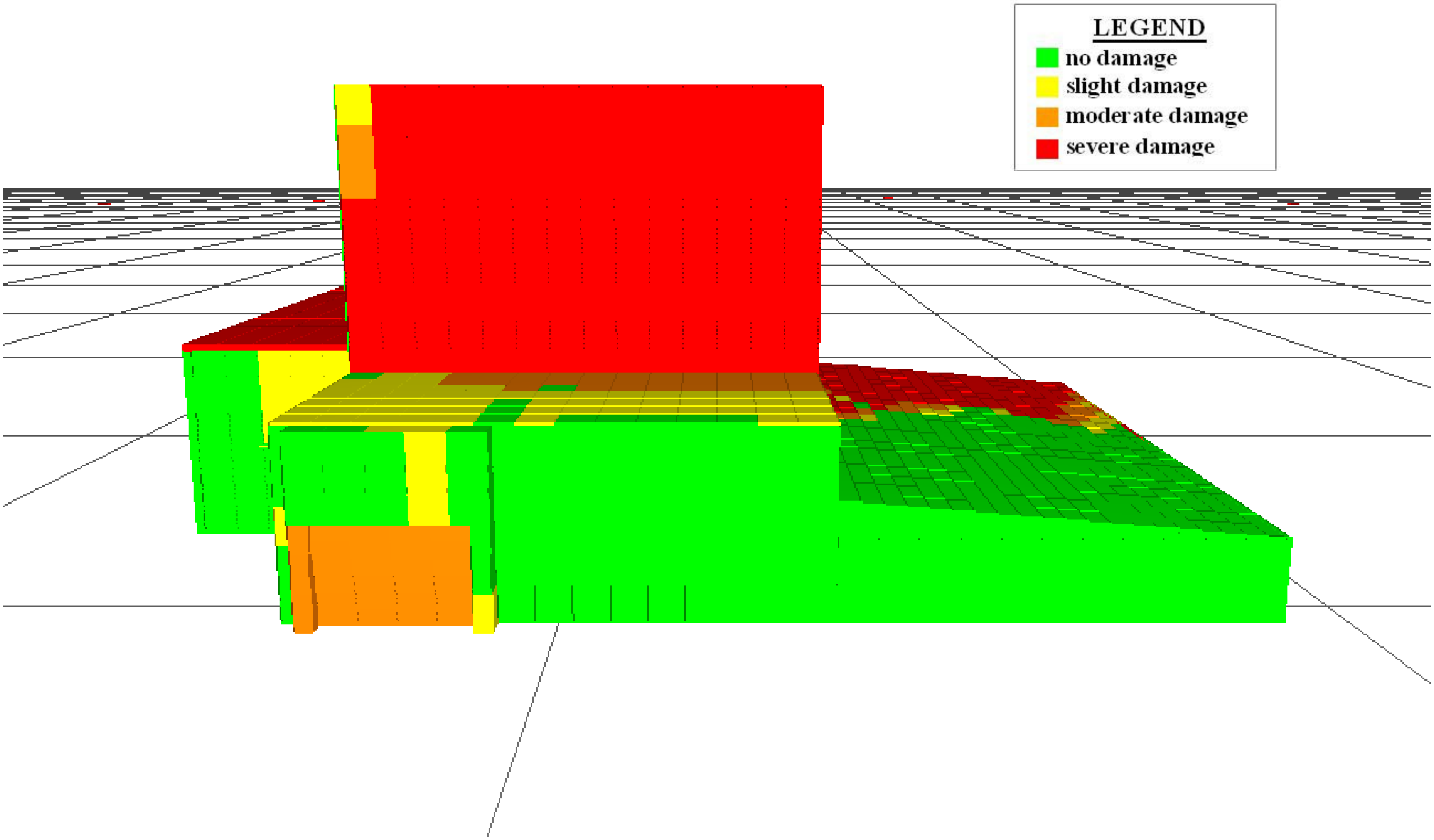

Figure 14. Damage Plot, MPPF West Face

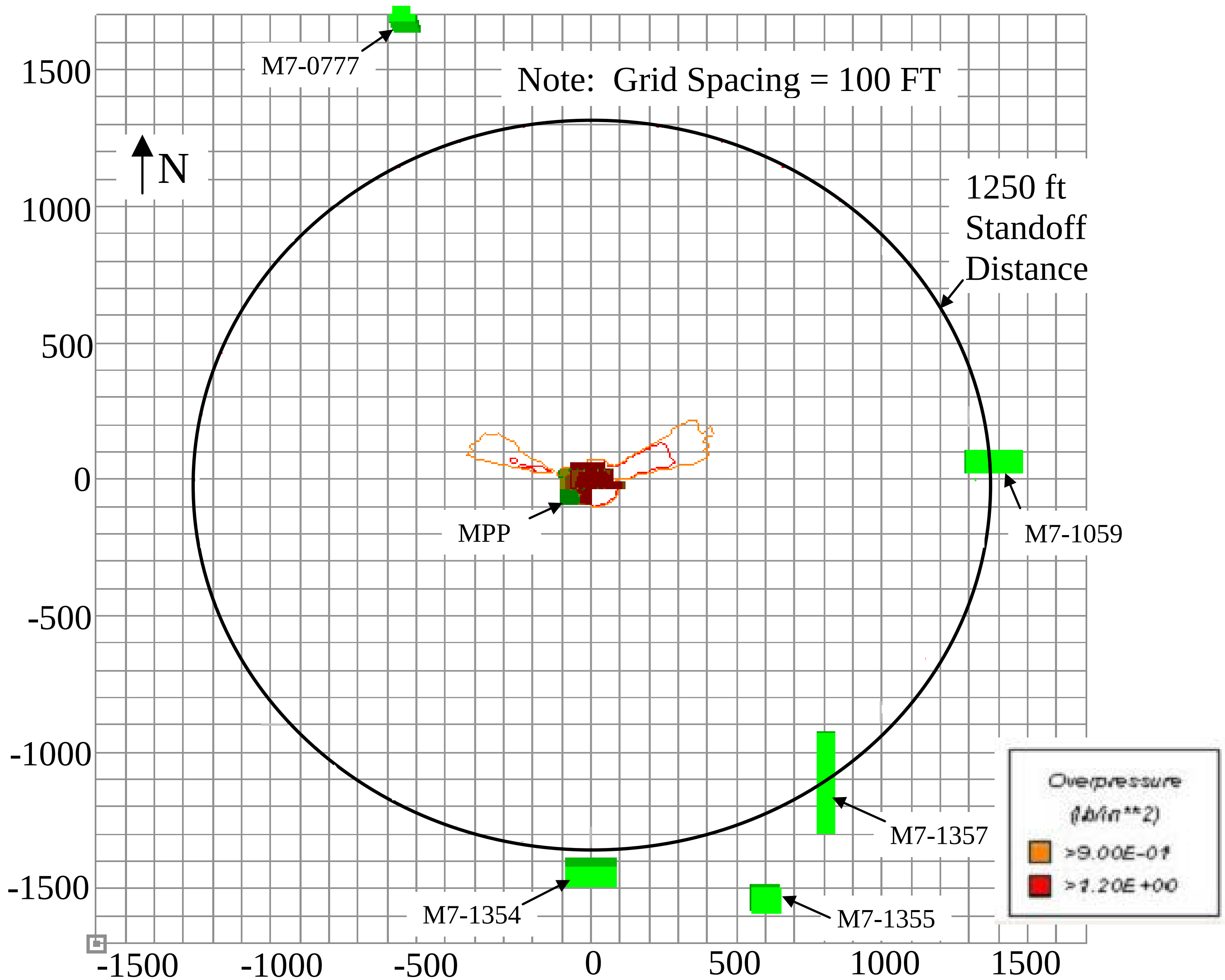

Figure 15. Horizontal Contour Plot, Overpressure (0.9 and 1.2 psi) Elevation 0 Ft.

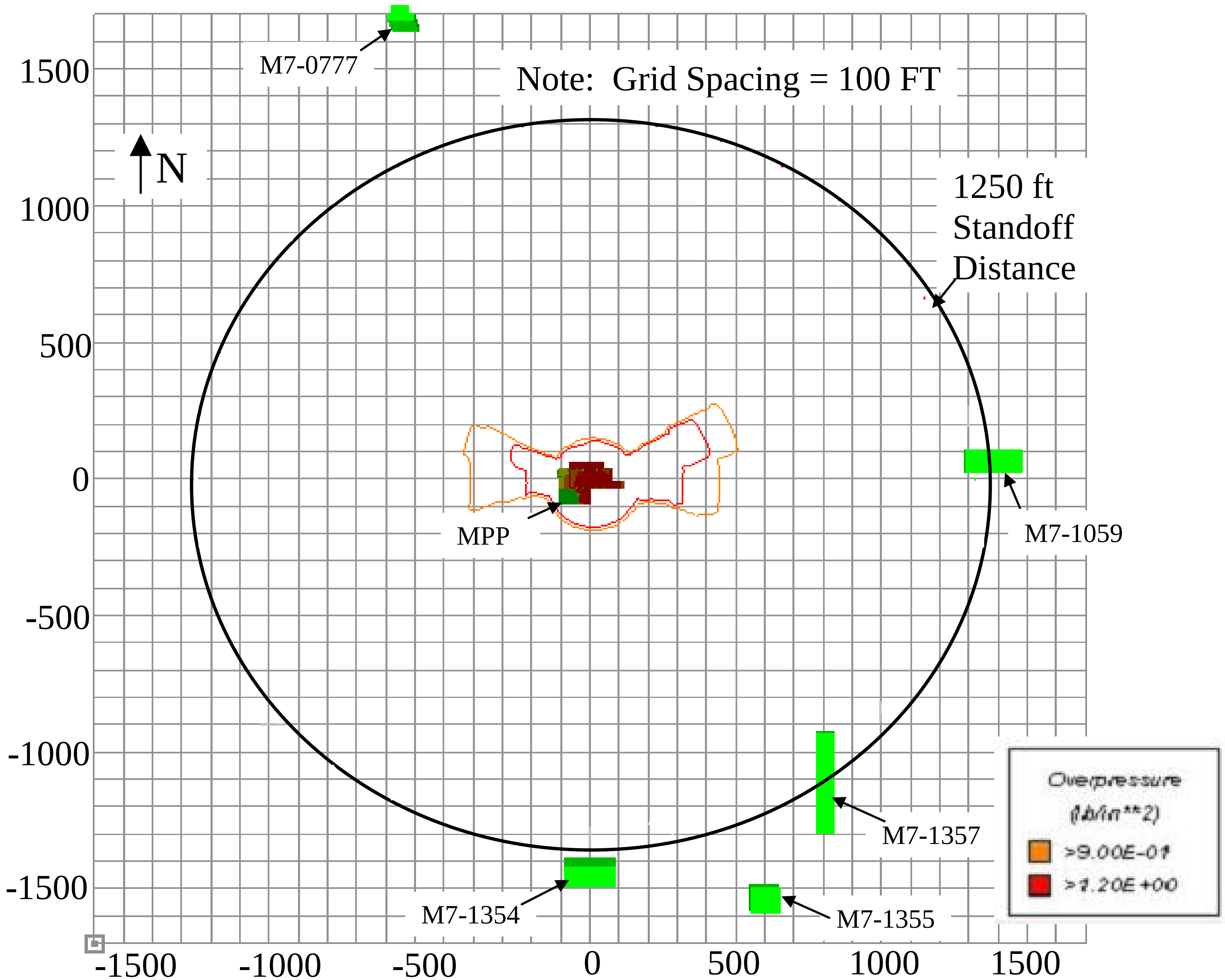

Figure 16. Horizontal Contour Plot, Overpressure (0.9 and 1.2 psi) Elevation 50 Ft.

4.0 PRIMARY FRAGMENTATION

The aluminum components within the CEV Service Module and Spacecraft Adapter were treated as a hollow cylinder which was the source of all primary fragments produced by the explosion. Characteristics of this cylindrical approximation are given in Table 2. Analyses of 88 different fragment paths were carried out by means of the PriFrag software [8]. A fragment drag coefficient of 1.2 was used in this analysis. The results indicated that 19.27% of the fragment paths were blocked by MPPF internal structures but the remaining primary fragments would impact and penetrate the MPPF wall at an elevation of approximately 18 feet. Such primary fragments were characterized by impact energies and number densities (as measured in a one-foot wide vertical plane extending from ground level up to an elevation of 6 feet), which remained hazardous at ranges out to 898 feet beyond the MPPF perimeter, as shown in Figure 17. These primary fragments appear to represent the most significant hazard to most surrounding buildings. A summary of primary fragmentation hazards is provided in Table 3.

Table 2. Cylindrical Approximation of CEV 606 Service Module and Space Craft Adapter for Primary Fragmentation

Cylinder Outside Diameter (ft)	18.223
Cylinder Height (ft)	16.8
Cylinder Wall Thickness (ft)	0.0366
Cylinder Composition	Aluminum
Cylinder Mass (lb_m)	
Spacecraft Adapter	2837.84
Service Module (.65 x 4780)	3107.00
Total	5944.84

Table 3. Summary of MPPF Primary Fragmentation Hazards

FACILITY #/NAME	HAZARDS
M7-1104/MPPF High Bay	Severe
M7-1104/MPPF North Office	Severe
M7-1104/MPPF Low Bay	Severe
M7-1104/MPPF Flight Data Control Room	Severe
M7-1104/MPPF Annex	Severe
M7-1357/Multi Operations Support Bldg (MOSB)	None-to-Slight
M7-1354/Payload Hazardous Servicing Facility (PHSF) Bldg	None-to-Slight
M7-1355/PHSF Storage Bay	None-to-Slight
M7-1059/Hypergolic Maintenance Facility	None-to-Slight
M7-0777/Canister Rotation Facility - High Bay	None-to-Slight
M7-0777/Canister Rotation Facility - Office Area	None-to-Slight

In carrying out this primary fragmentation analysis a discrepancy in the value of fragment drag coefficient was detected and corrected. This discrepancy resulted from the fact that in certain

standard references [6, 9-14] a value of 0.6 (instead of 1.2) was recommended for primary fragment drag coefficient. This value, however, was based on a nonstandard definition of drag, in which a factor of one-half had been omitted. In two earlier studies of explosions in the MPPF [15, 16] this smaller value had been used, resulting in the prediction of significantly greater hazardous primary fragmentation ranges.

5.0 SECONDARY FRAGMENTATION

The secondary (internal) fragments were produced by the interaction of the blast wave inside the MPPF high bay interacting with the CEV Access Stand. The generation of secondary (internal) fragments is very dependent on the composition and configuration of the internal structures within the MPPF High Bay. Because of their proximity to the explosion, secondary (internal) fragments tend to be more energetic then secondary (external) fragments, which tend to be more removed from the explosion. The HEXFRAG software [17] was used to carry out the analysis along the 21 different fragment paths, shown in Figure 18. Along 3 of the paths the secondary (internal) fragments impacting the MPPF wall did not possess hazardous impact energies and could not penetrate the MPPF wall. Fragments along the remaining 18 paths did possess hazardous impact energy, and their impact velocity was sufficient to penetrate the MPPF wall.

The secondary (external) fragments were produced by the interaction of the blast wave with the external frangible components of the MPPF high bay, where moderate or severe damage was produced. For purposes of the secondary (external) fragmentation analysis, the MPPF wall was assumed to consist of a sheet of corrugated steel. The HEXFRAG software was used with this assumption to carry out the analysis along the same 21 fragment paths previously noted.
The results from the HEXFRAG runs for the secondary (internal) fragments were combined with the secondary (external) fragment results to obtain the total secondary fragment hazardous ranges. As shown in Figure 19, such ranges extended out no more than 420 feet beyond the MPPF perimeter. Such fragments appear to pose a significant hazard to the MPPF itself but no hazard to any nearby KSC structures. A summary of secondary fragmentation hazards is provided in Table 4.

Table 4. Summary of MPPF Secondary Fragmentation Hazards

FACILITY #/NAME	HAZARDS
M7-1104/MPPF High Bay	Severe
M7-1104/MPPF North Office	Moderate-to-Severe
M7-1104/MPPF Low Bay	Moderate-to-Severe
M7-1104/MPPF Flight Data Control Room	Moderate-to-Severe
M7-1104/MPPF Annex	Moderate-to-Severe
M7-1357/Multi Operations Support Bldg (MOSB)	None
M7-1354/Payload Hazardous Servicing Facility (PHSF) Bldg	None
M7-1355/PHSF Storage Bay	None
M7-1059/Hypergolic Maintenance Facility	None
M7-0777/Canister Rotation Facility - High Bay	None
M7-0777/Canister Rotation Facility - Office Area	None

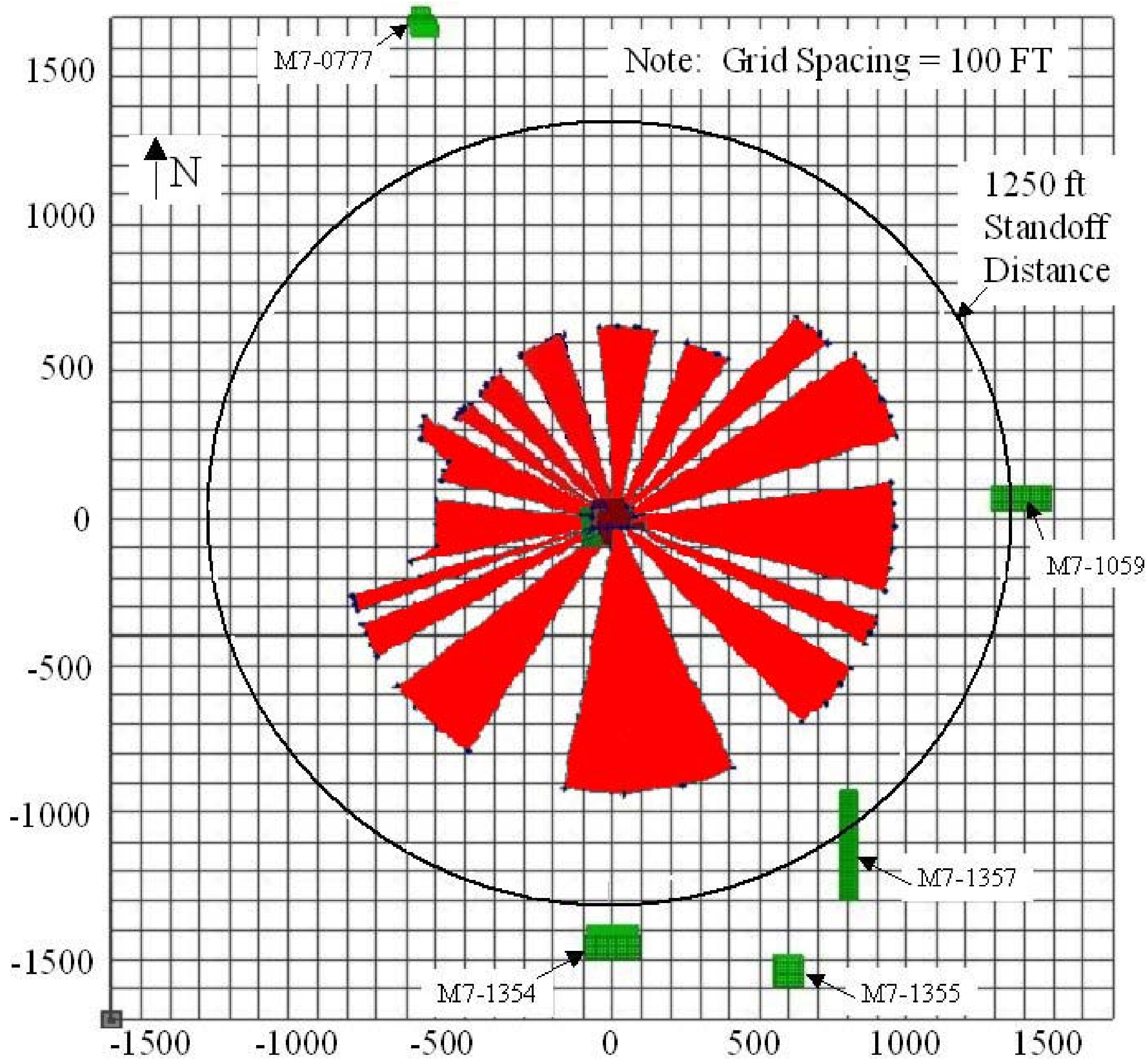

Figure 17. Primary Hazardous Fragment Range Distribution

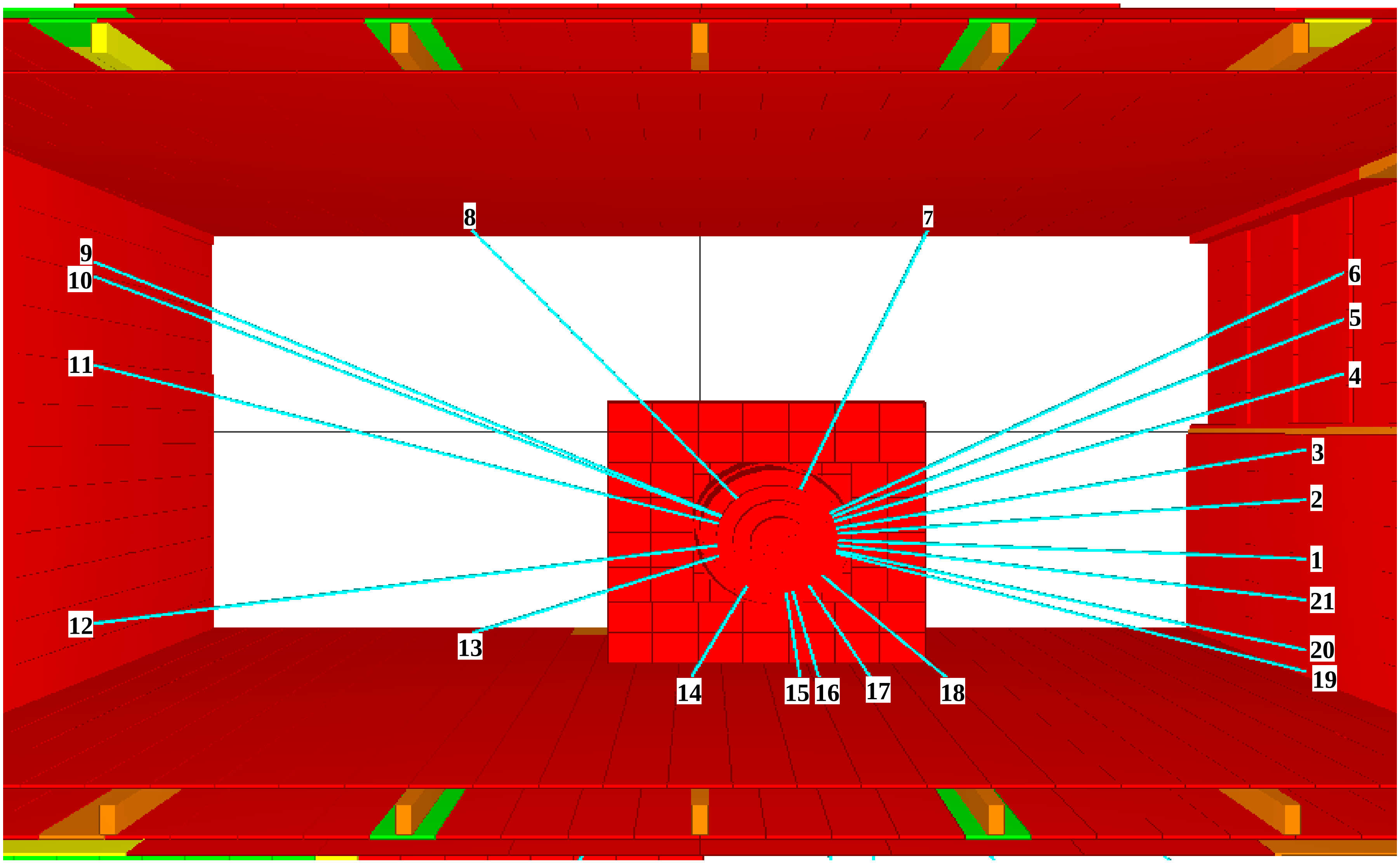

Figure 18. Secondary Fragment Paths for MPPF

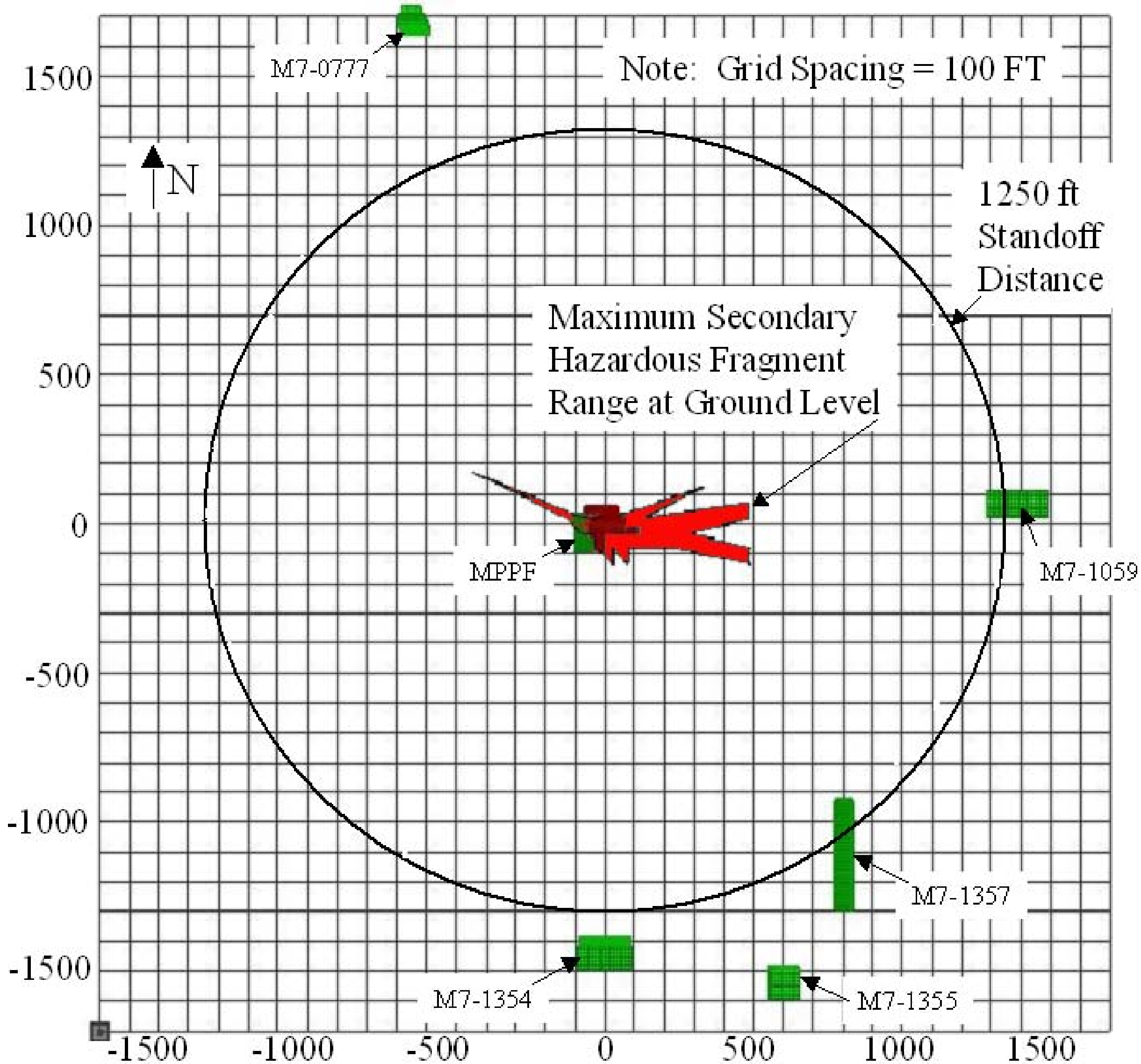

Figure 19. Secondary Hazardous Fragment Range Distribution

6.0 CONCLUSIONS

Based on the results of the analyses described in Section 2.0 through 5.0, the following conclusions are reached:

1) Blast hazards are limited primarily to the MPPF.
2) Primary fragment hazards represent the greatest concern to surrounding KSC buildings with ranges extending out to 898 feet beyond the MPPF perimeter.

Secondary hazardous fragment ranges extend out no more than 420 feet and pose minimal hazard to nearby KSC structures.

7.0 REFERENCES CITED

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ANALYSIS OF POSSIBLE EXPLOSION AT KSC DUE TO SPONTANEOUS IGNITION OF HYPERGOLIC PROPELLANTS

by
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July 13, 2009

BACKGROUND

- ENGINEERING ANALYSIS INC. (EAI) CARRIED OUT EXPLOSIVE SAFETY STUDIES
  - UNDER SUBCONTRACT WITH ASRC AEROSPACE INC.
  - UNDER SUPERVISION OF EXPLOSIVE SAFETY OFFICE, NASA, KSC

- CONCERNED WITH ORION CREW EXPLORATION VEHICLE (CEV)
  - PART OF ARES SPACECRAFT
  - TWO COMPONENTS TO BE PROCESSED OFFLINE
    - CREW MODULE (CM)
    - SERVICE MODULE (SM)

- OFFLINE PROCESSING
  - INVOLVES SERVICING OF SM WITH 18,000 POUNDS OF HYPERGOLIC FUEL
  - CONVENTIONAL QD CALCULATIONS NO LONGER VIABLE

BACKGROUND (cont.)

- PRIMARY CONCERN: SPONTANEOUS IGNITION OF HYPERGOLIC PROPELLANT
- FACILITIES INCLUDED IN EXPLOSIVE SAFETY STUDIES
  - VEHICLE ASSEMBLY BUILDING (VAB)
  - MULTI-PAYLOAD PROCESSING FACILITY (MPPF)
  - CANISTER ROTATION FACILITY (CRF)
- SUBSEQUENT DISCUSSION DEALS WITH MPPF ANALYSIS

STATEMENT OF PROBLEM

- PREDICT BLAST AND FRAGMENTATION EFFECTS PRODUCED BY THE EXPLOSION OF THE HYPERGOLIC FUELS CONTAINED IN THE CREW EXPLORATION VEHICLE (CEV 606) SERVICE MODULE IN THE MULTI-PAYLOAD PROCESSING FACILITY (MPPF).

- COMPARE RESULTS WITH CURRENT STANDOFF DISTANCE OF 1250 FT FROM OUTER PERIMETER OF MPPF.

FIGURE 1. MULTI-PAYLOAD PROCESSING FACILITY (MPPF)

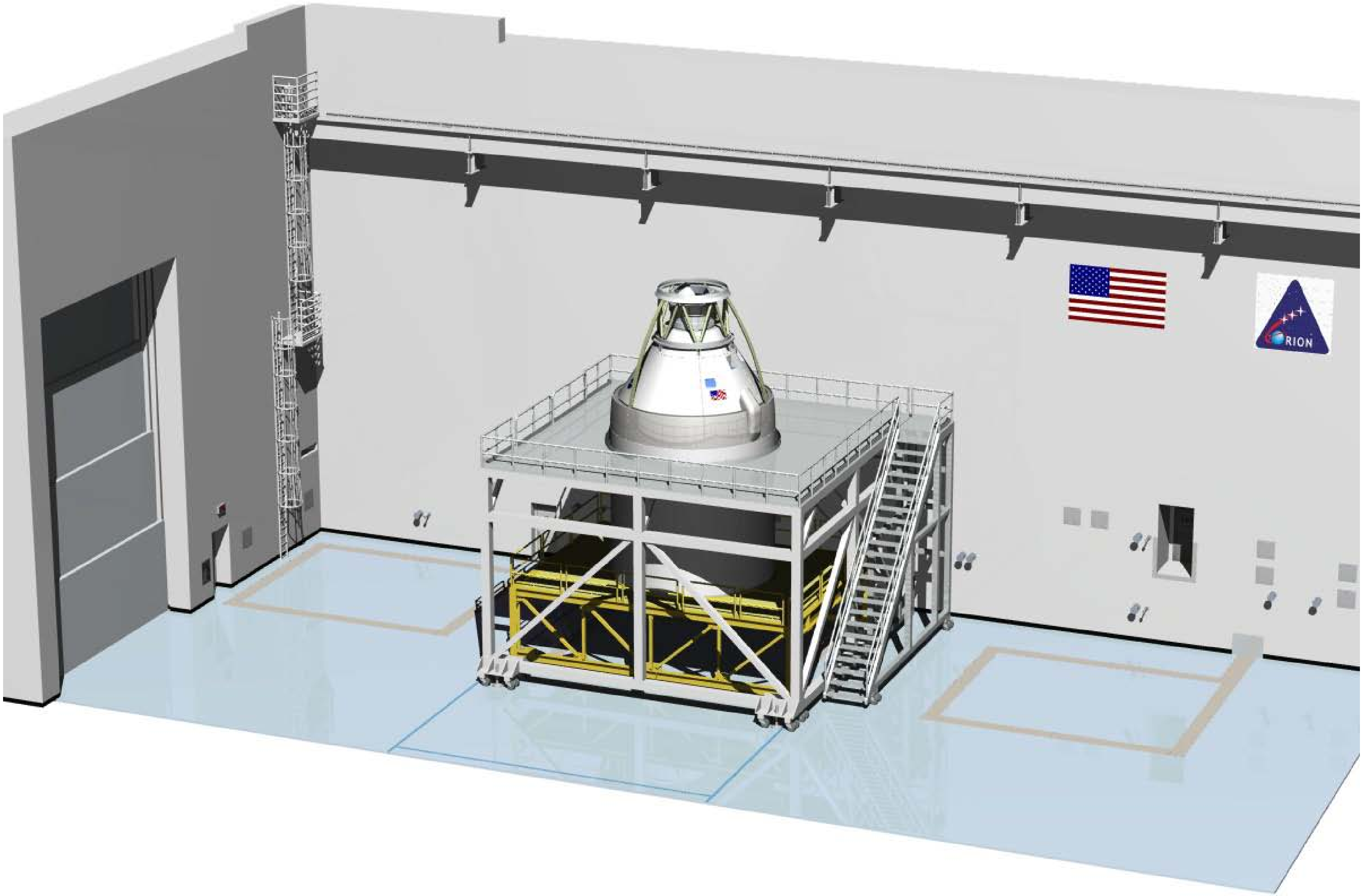

FIGURE 2. CEV 606 SHORT STACK SURROUNDED BY ACCESS STAND POSITIONED WITHIN MPPF HIGHBAY

SAFETY STANDARDS [1,2,3,4]

- **OVERPRESSURE LIMITS FOR INHABITED BUILDING: 0.9 - 1.2 PSI**

- **FRAGMENTATION LIMITS**
  - **IMPACT ENERGY: LESS THAN 58 FT-LB_f**
  - **HAZARDOUS FRAGMENT DENSITY:**
    - **LESS THAN 1 FRAGMENT/600 FT^2**
    - **IN VERTICAL PLANE**
      - **ONE FOOT WIDE**
      - **EXTENDING FROM GROUND LEVEL UP TO SIX FT**

- **INHABITED BUILDING DISTANCE: 1250 FT, MEASURED FROM PERIMETER OF BUILDING CONTAINING EXPLOSIVE**

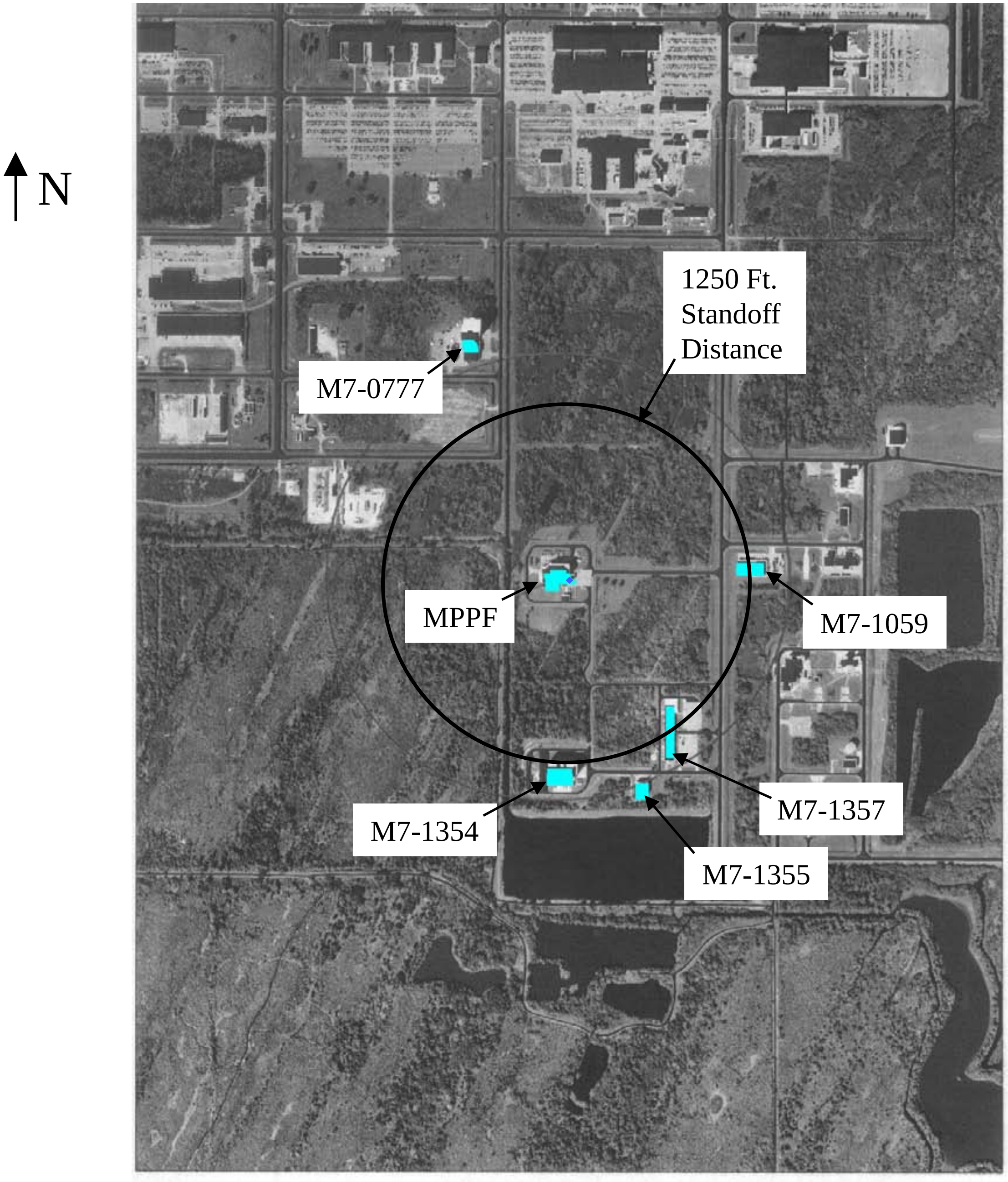

FIGURE 3. KSC BUILDINGS IN VICINITY OF MPPF

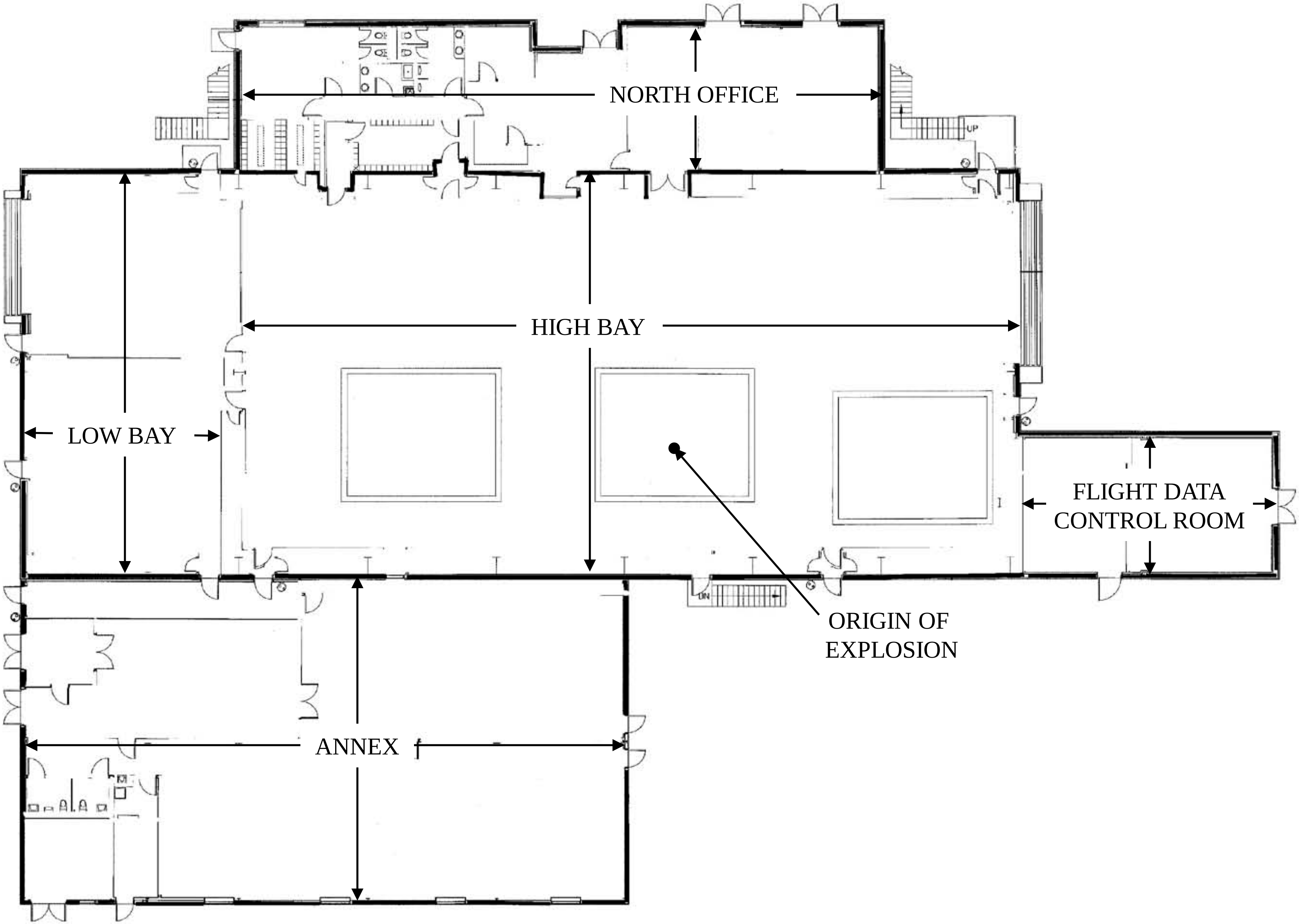

FIGURE 4. MPPF PLAN VIEW

PROBLEM BREAKDOWN

- **BLAST EFFECTS**
- **FRAGMENTATION EFFECTS**
  - **PRIMARY**
  - **SECONDARY**

CALCULATION OF BLAST EFFECTS

- **TECHNICAL APPROACH - BASED ON HEXDAM SOFTWARE [6]**
- **RESULTS**
  - **DAMAGE TO STRUCTURES**
  - **OVERPRESSURE CONTOURS**

EXPLOSION CHARACTERISTICS

- MASS OF HYPERGOLIC PROPELLANT (LB_m)
  - ACTUAL - 17,992.4
  - 20% DGM* - 3,598.5
  - TOTAL 21,590.9

- ASSUMED TNT EQUIVALENT (5.0%) (LB_m): 1,079.54

- LOCATION: POSITIONED ON PLATFORM IN ACCESS STAND IN MPPF HIGH BAY

- COORDINATES (FT)
  - X = 8.366
  - Y = -13.189
  - Z = 20.908

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*Design Growth Margin

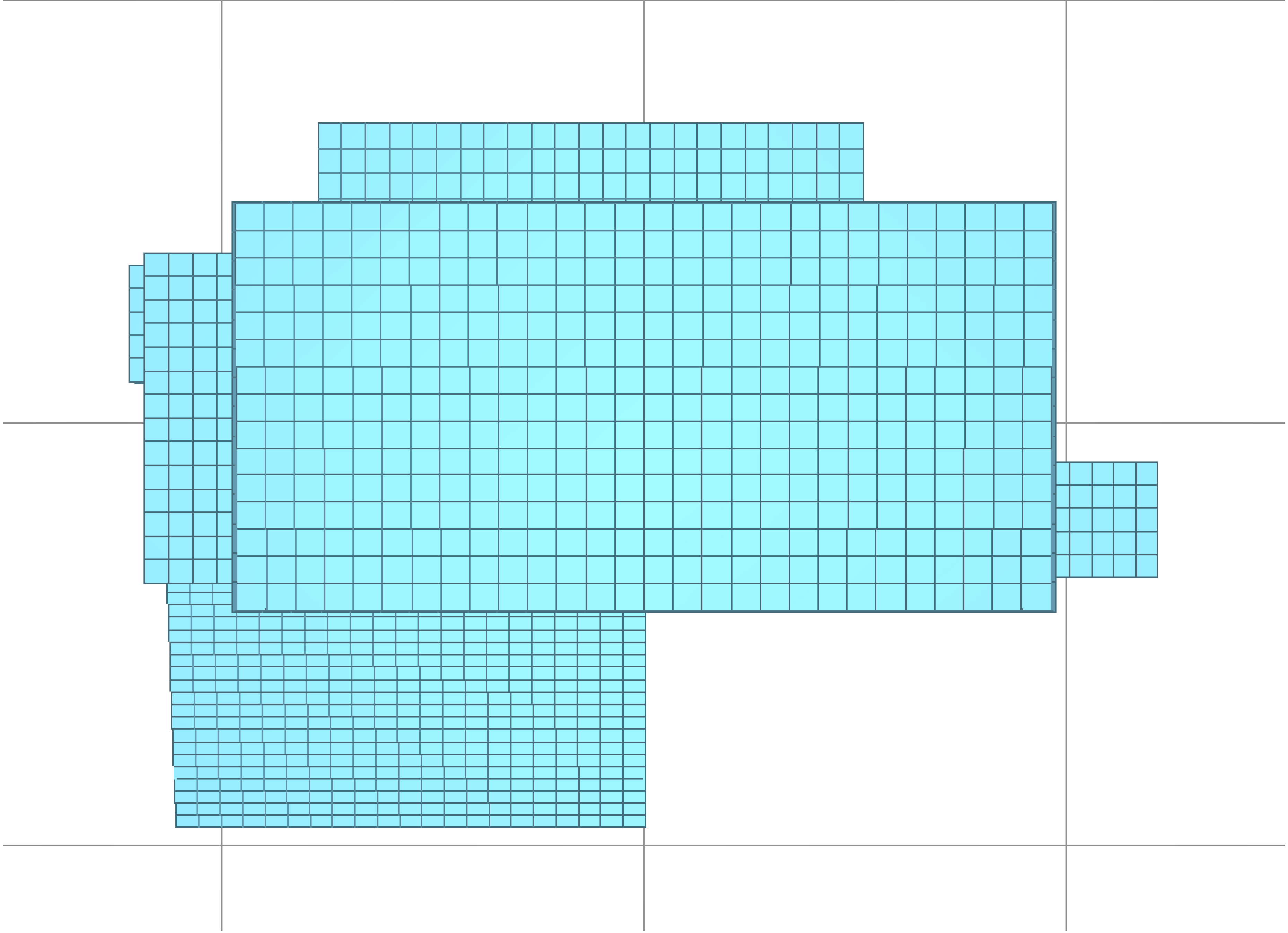

FIGURE 5. MPPF ROOF

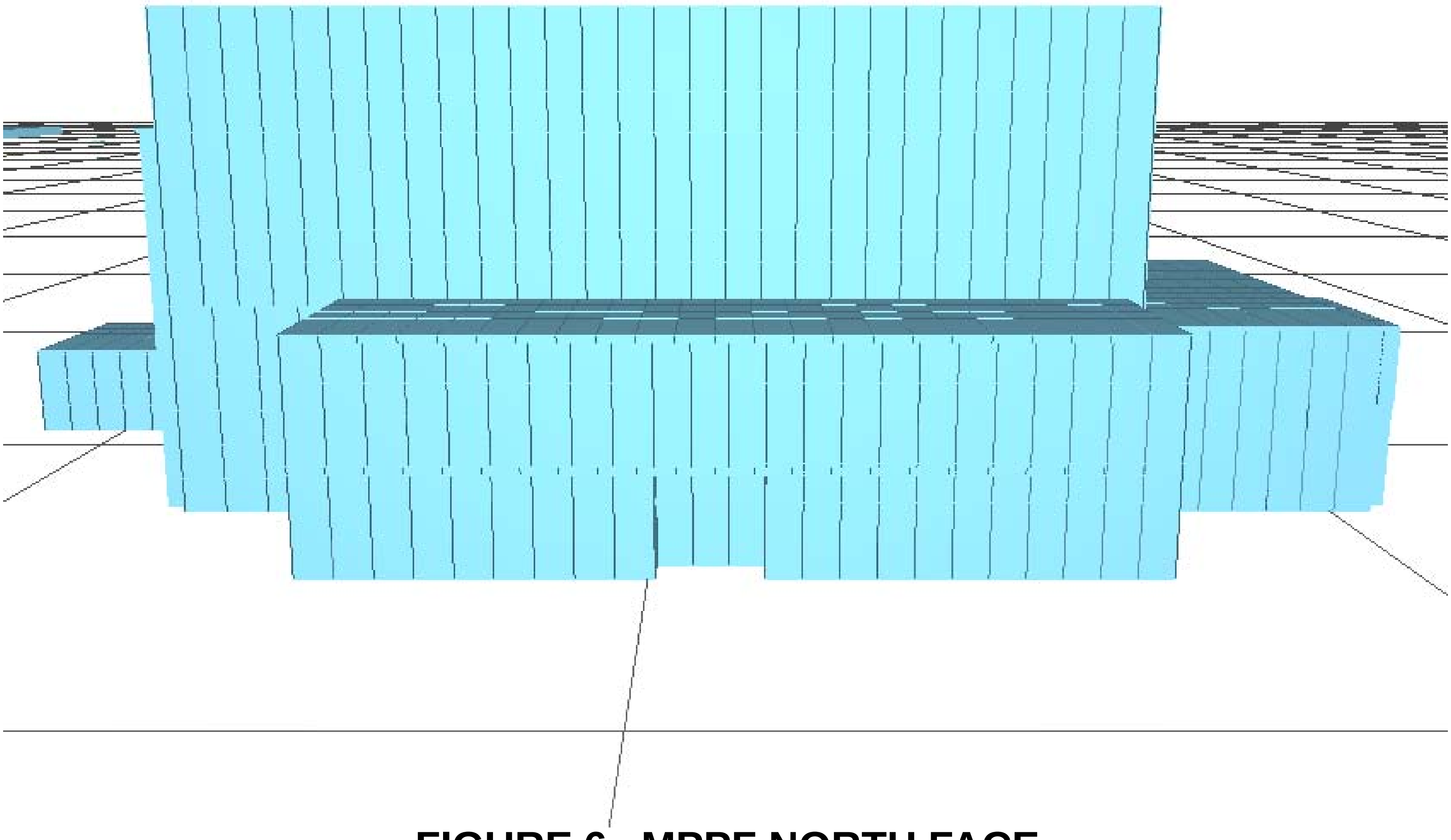

FIGURE 6. MPPF NORTH FACE

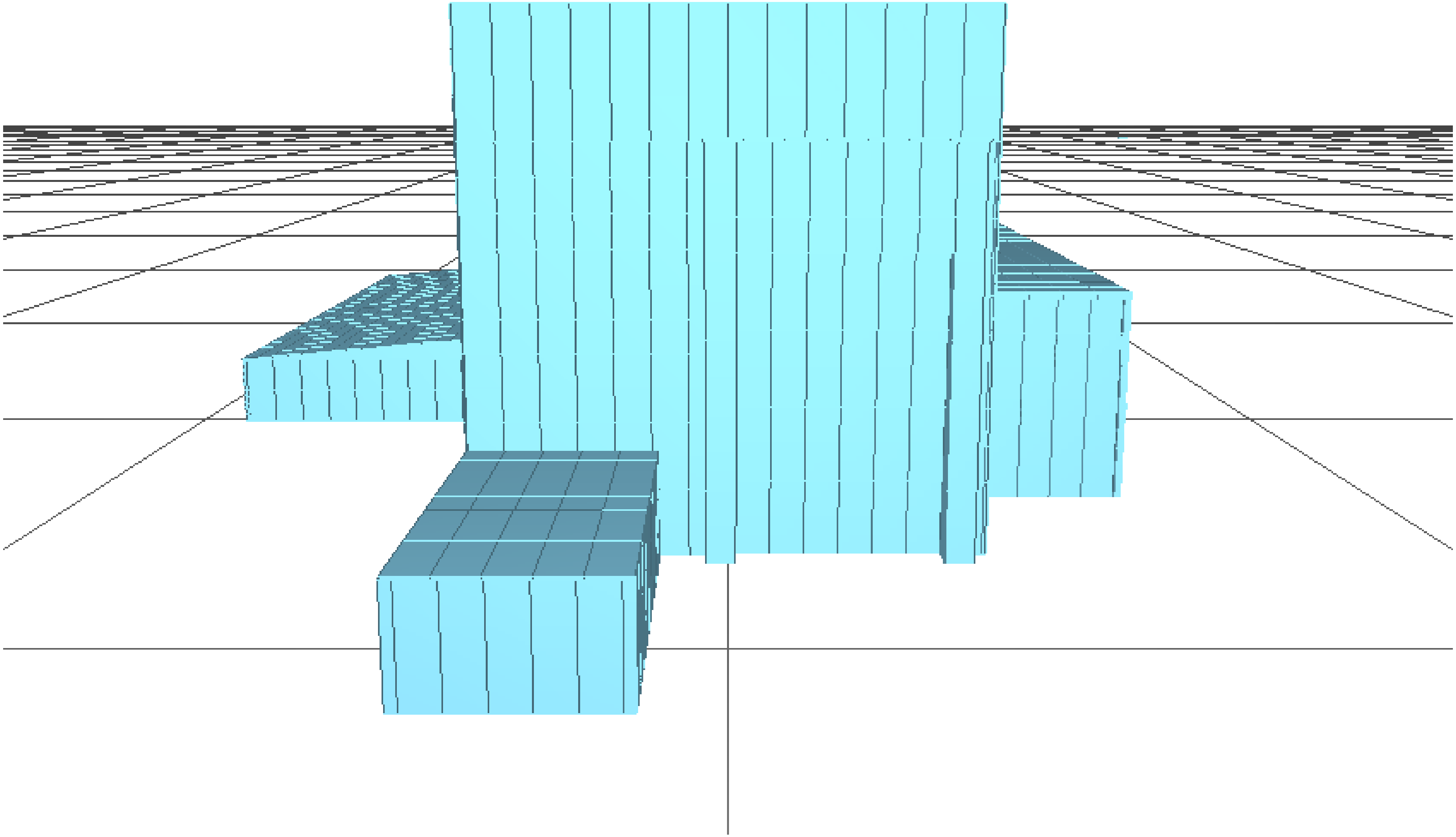

FIGURE 7. MPPF EAST FACE

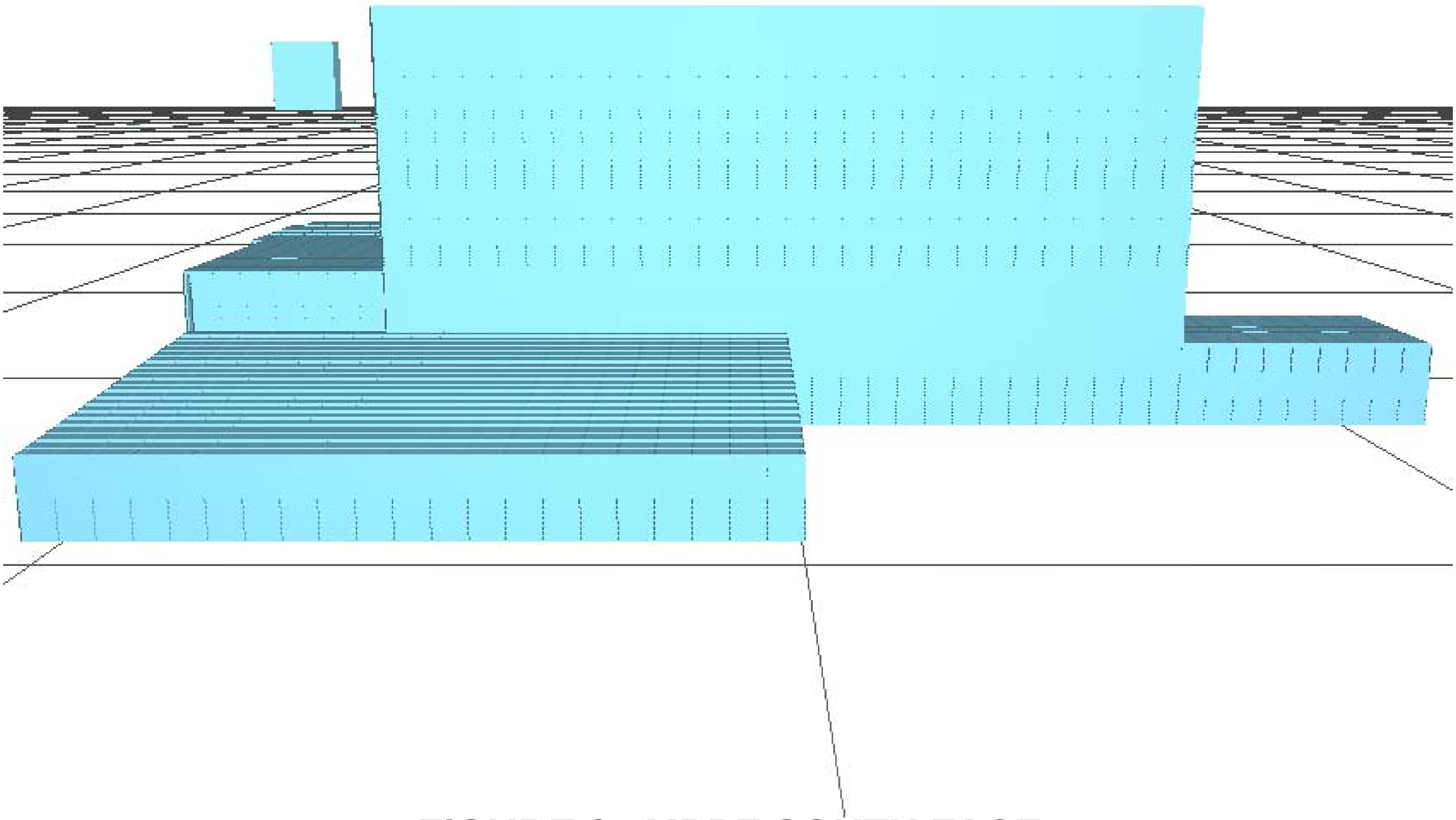

FIGURE 8. MPPF SOUTH FACE

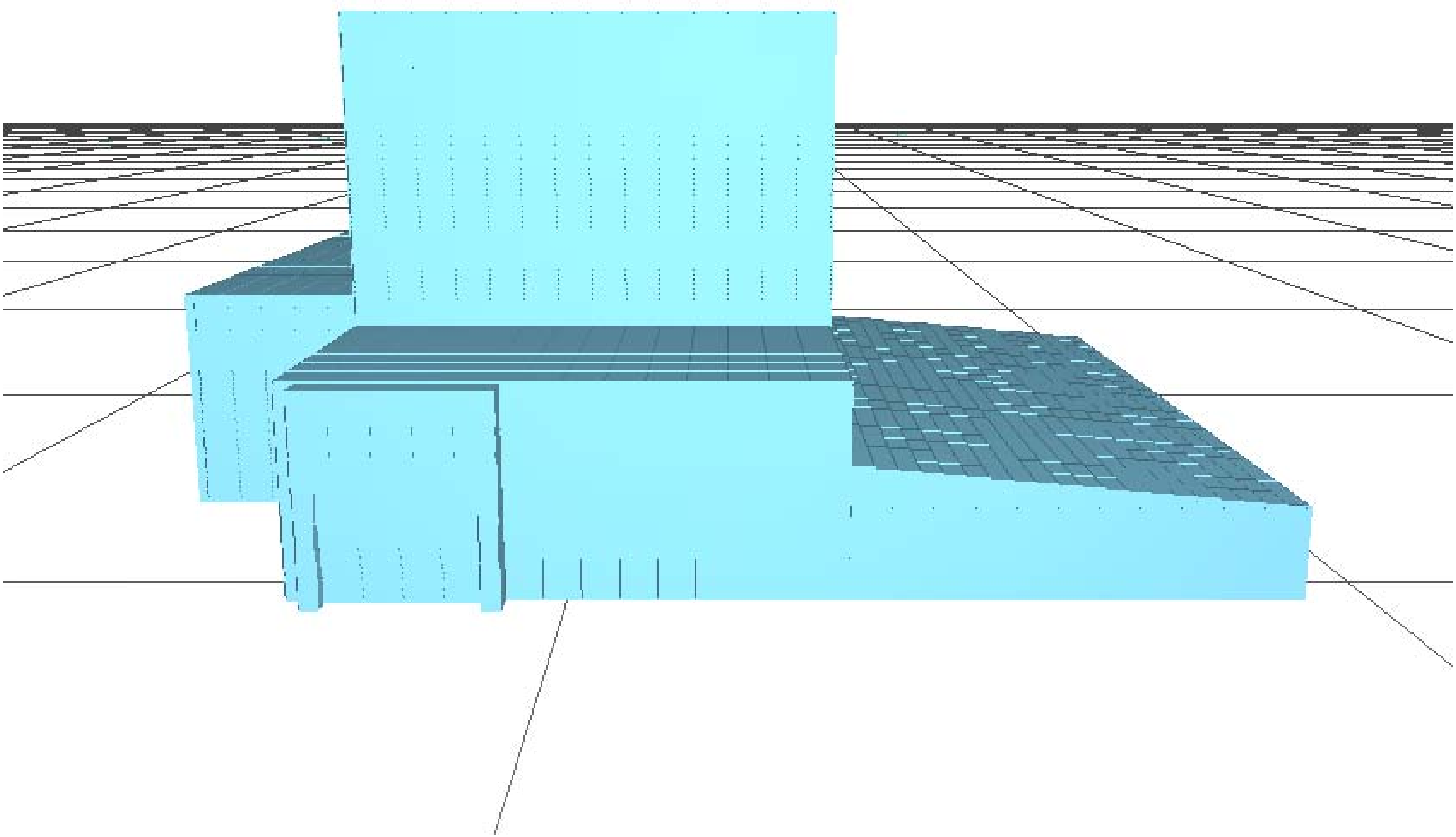

FIGURE 9. MPPF WEST FACE

INDEX OF GRAPHICAL RESULTS WITH BLAST DAMAGE

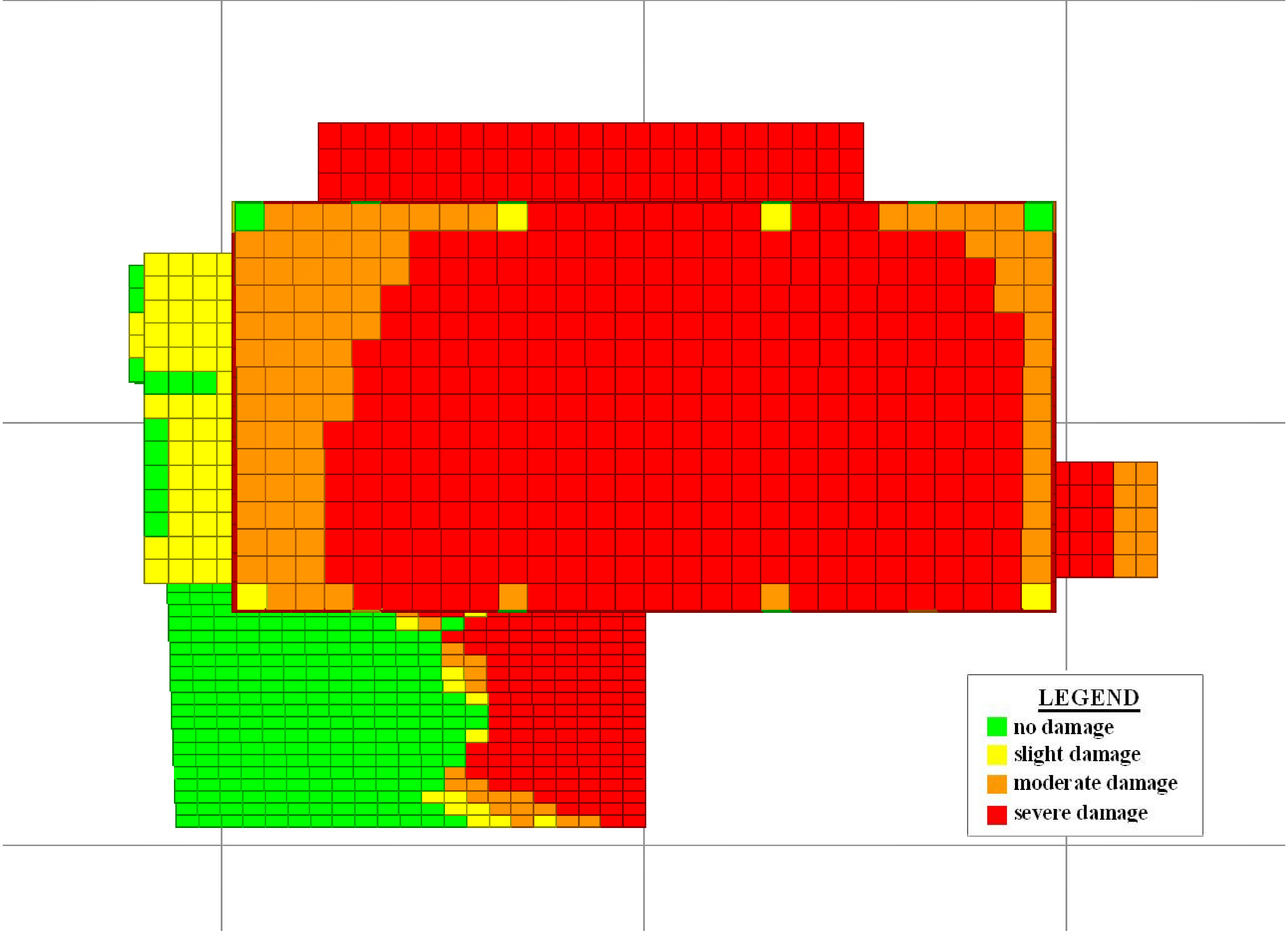

FIGURE 10. DAMAGE PLOT, MPPF ROOF

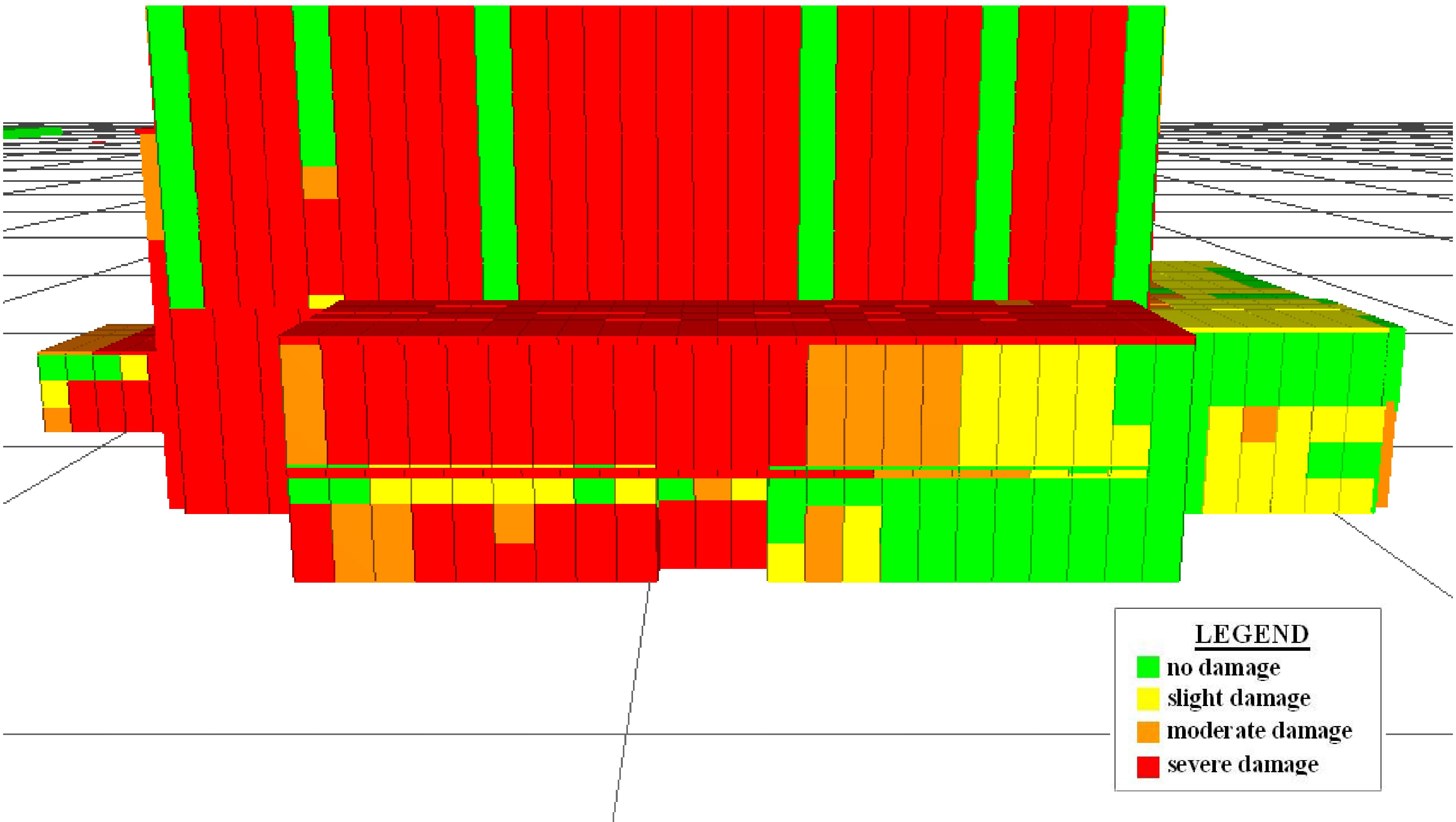

FIGURE 11. DAMAGE PLOT, MPPF NORTH FACE

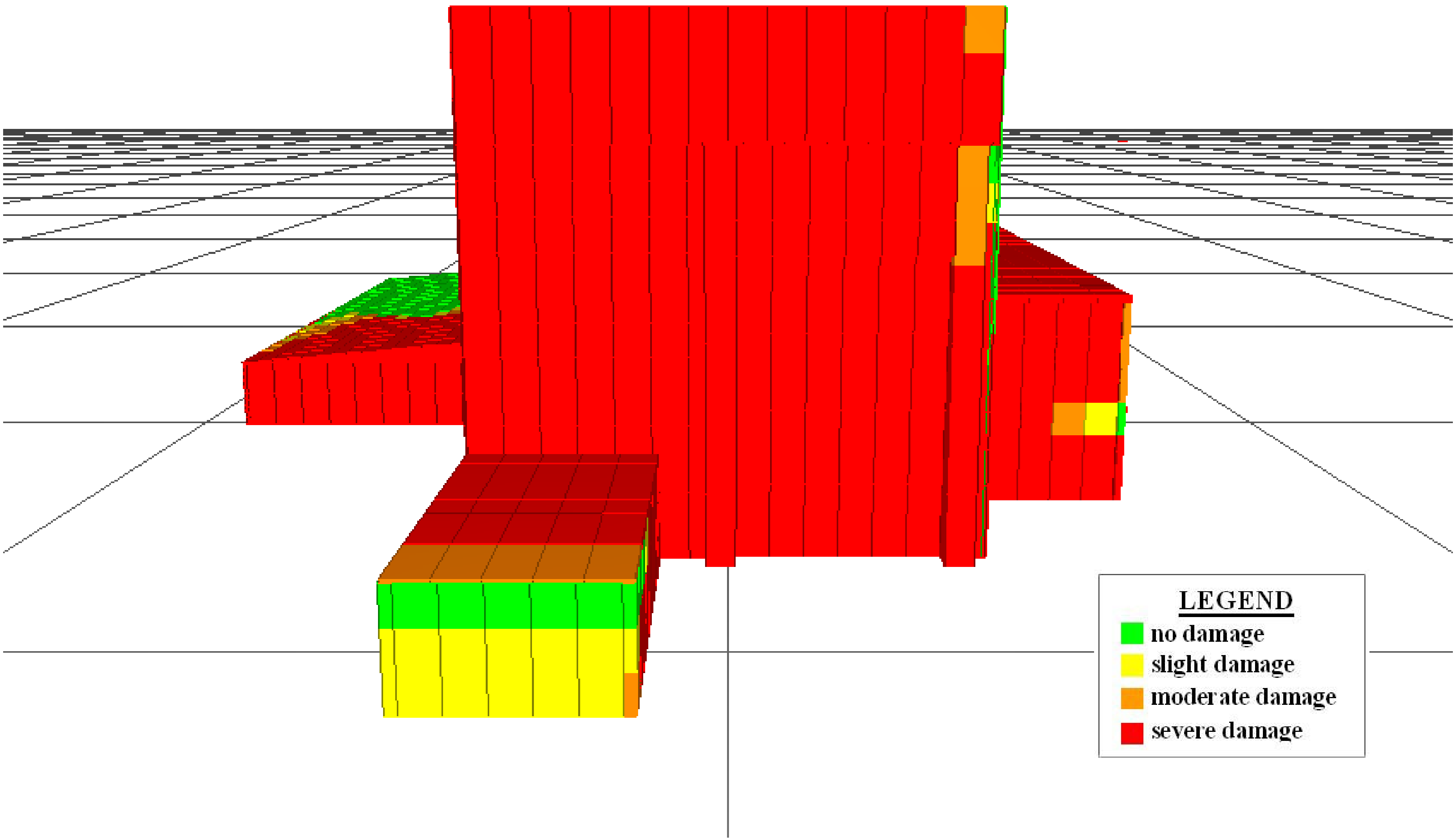

FIGURE 12. DAMAGE PLOT, MPPF EAST FACE

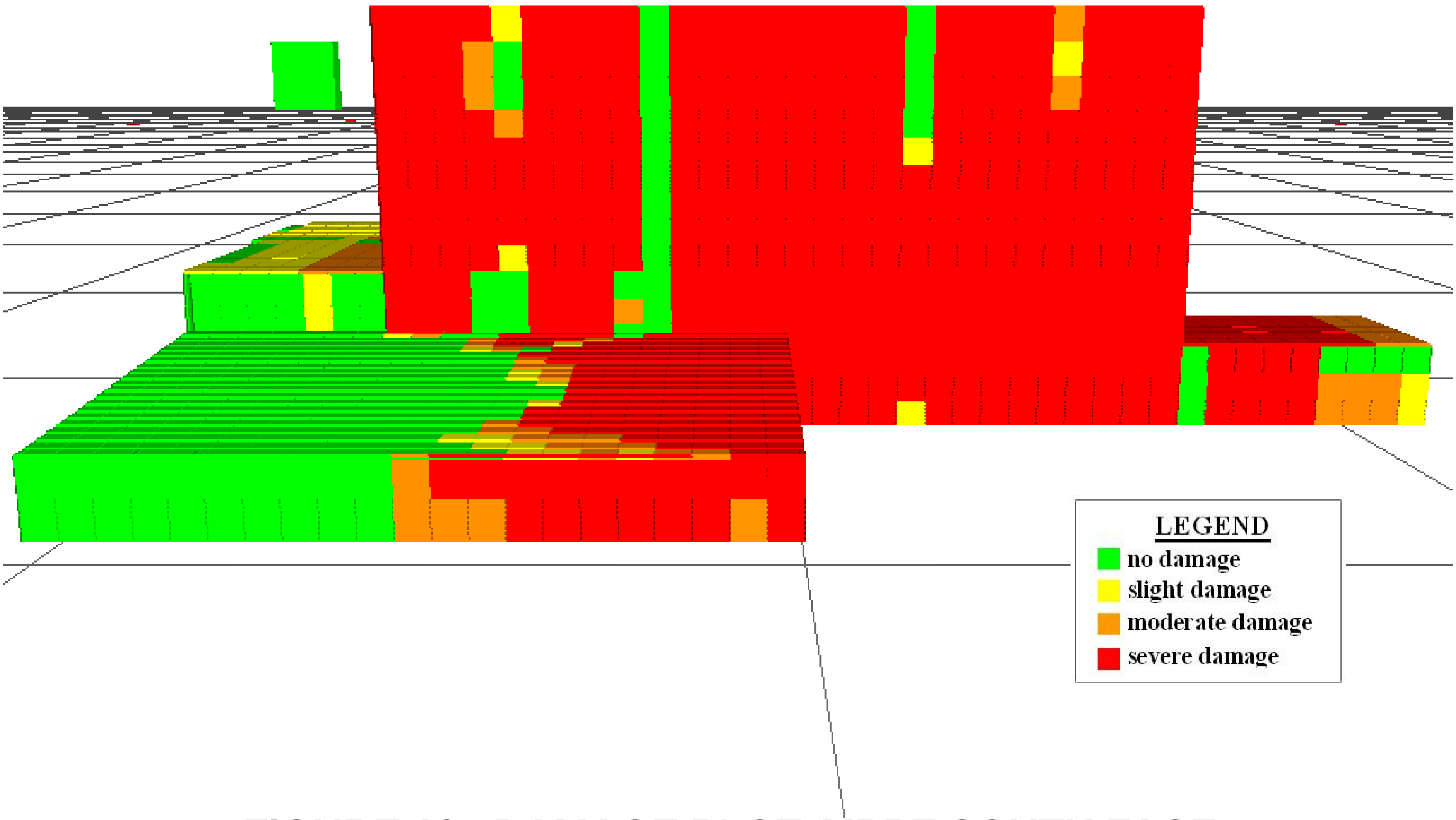

FIGURE 13. DAMAGE PLOT, MPPF SOUTH FACE

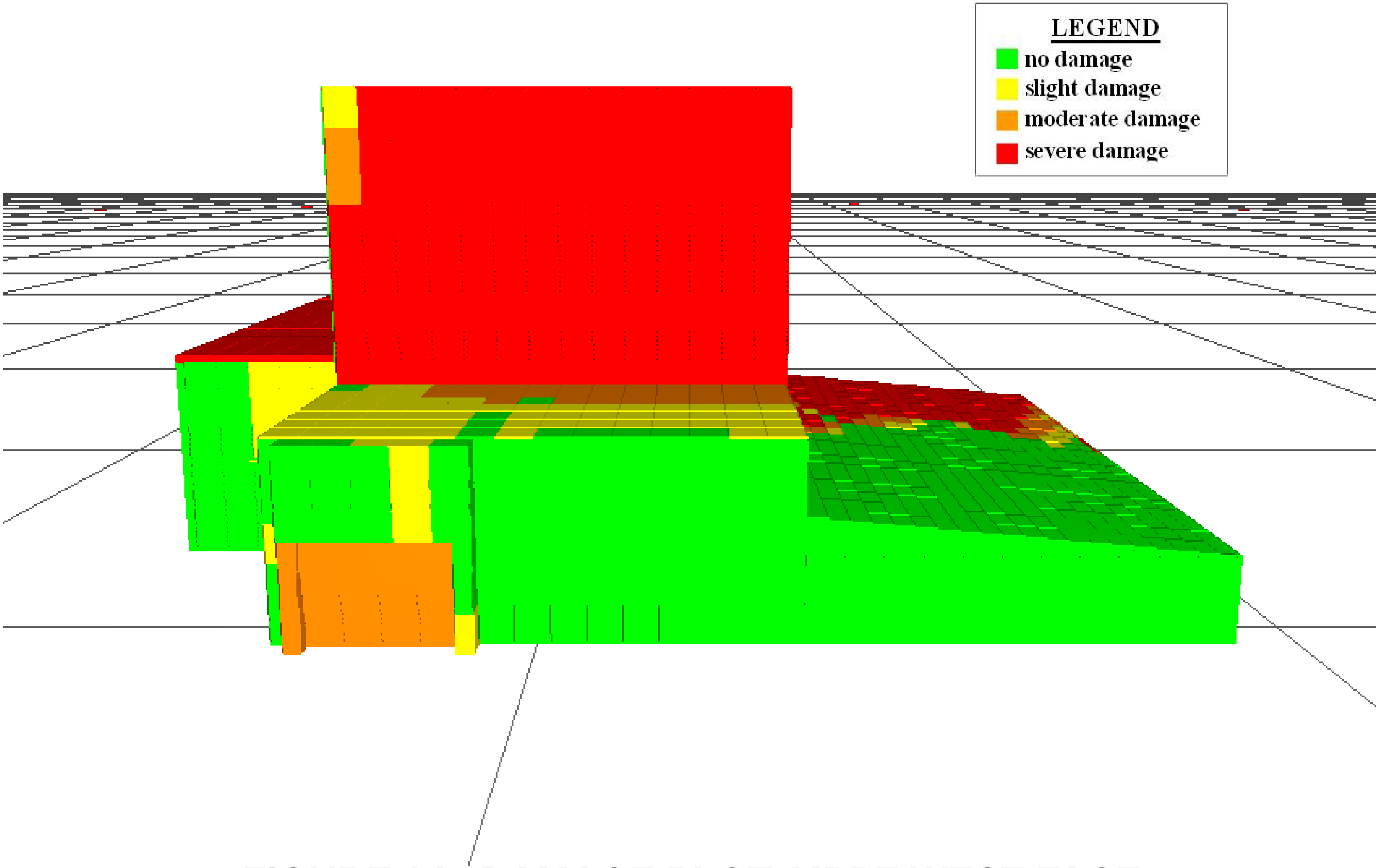

FIGURE 14. DAMAGE PLOT, MPPF WEST FACE

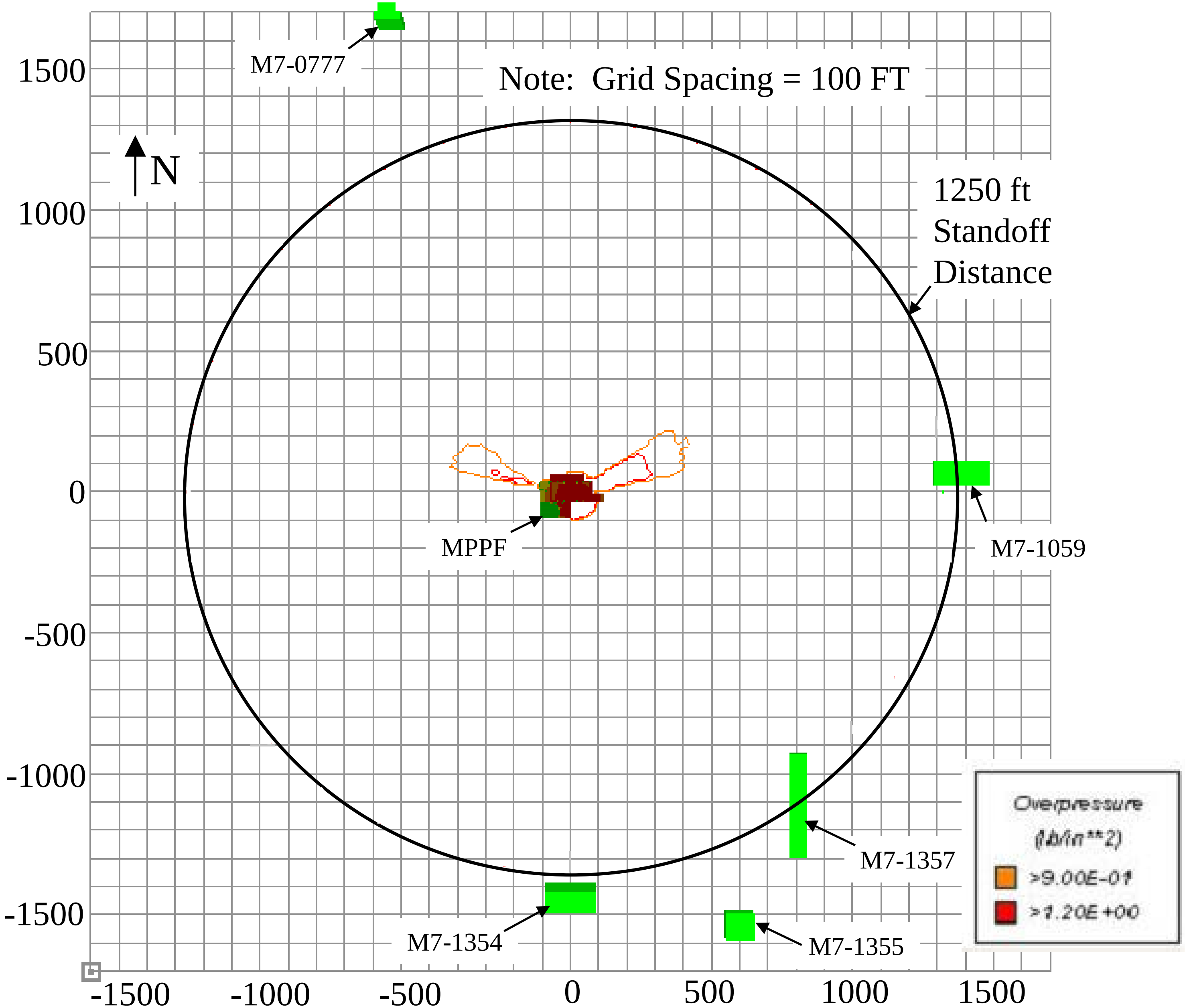

FIGURE 15. HORIZONTAL CONTOUR PLOT, OVERPRESSURE (0.9 AND 1.2 PSI) ELEVATION 0 FT

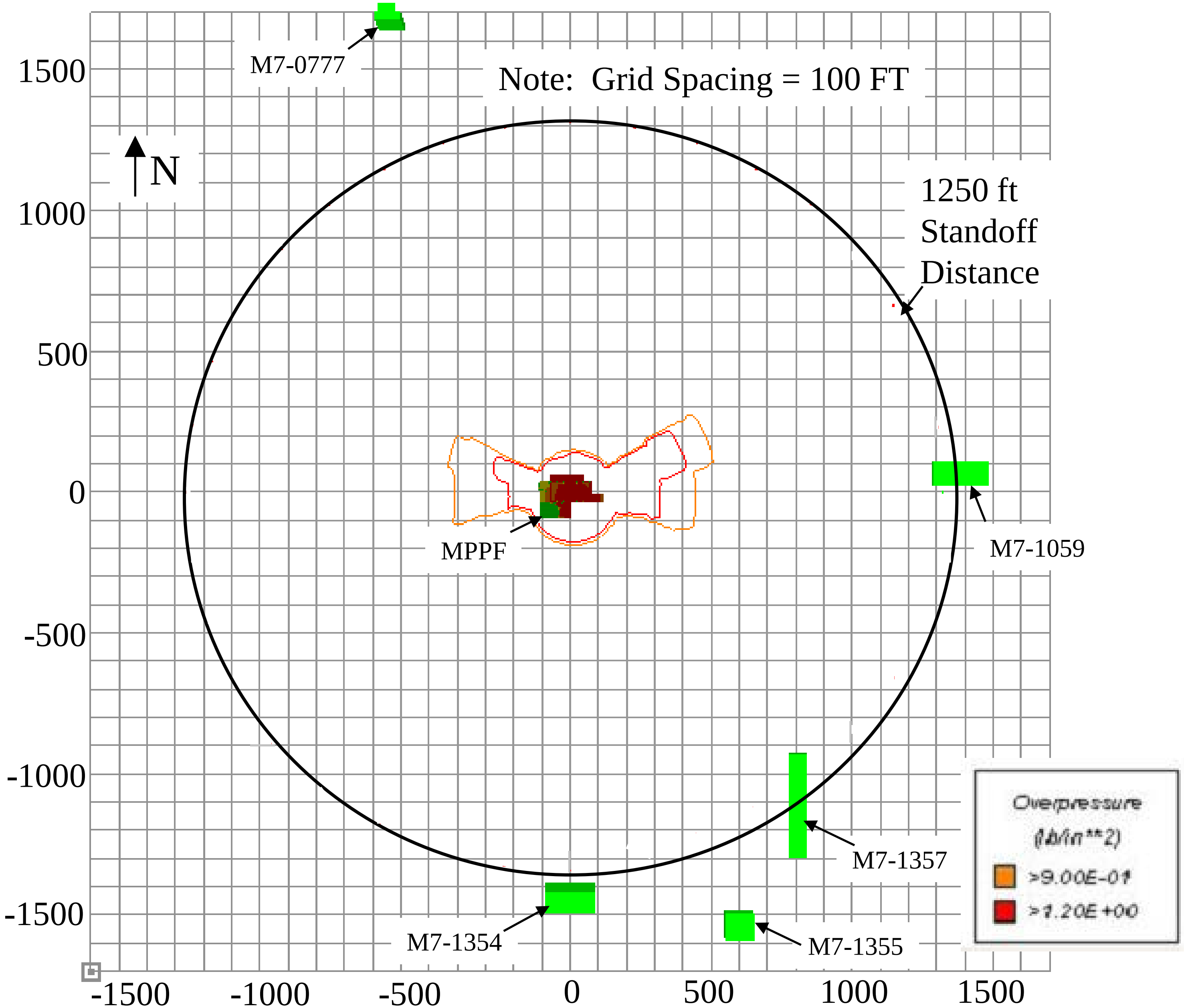

FIGURE 16. HORIZONTAL CONTOUR PLOT, OVERPRESSURE (0.9 AND 1.2 PSI) ELEVATION 50 FT

CALCULATION OF PRIMARY FRAGMENTATION EFFECTS

- TECHNICAL APPROACH - BASED ON PRIFRAG SOFTWARE

- RESULTS
  - PRIMARY FRAGMENT CHARACTERISTICS
  - PRIMARY FRAGMENT PATHS
  - HAZARDOUS FRAGMENT
    - VELOCITIES
    - RANGES
    - NUMBER DENSITIES

CYLINDRICAL APPROXIMATION OF CEV 606 SERVICE MODULE AND SPACE CRAFT ADAPTER FOR PRIMARY FRAGMENTATION

- **CYLINDER OUTSIDE DIAMETER (ft) - 18.223**
- **CYLINDER HEIGHT (ft) - 16.8**
- **CYLINDER WALL THICKNESS (ft) - 0.0366**
- **CYLINDER COMPOSITION - ALUMINUM**
- **CYLINDER MASS (lb_m)**
  - **SPACECRAFT ADAPTER - 2837.84**
  - **SERVICE MODULE (.65 x 4780) - 3107.00**

  TOTAL - 5944.84
- **ALUMINUM DENSITY (lb_m/ft^3) - 169**
- **ELEVATION ABOVE GROUND LEVEL (ft)**
  - **BASE OF CYLINDER - 9.62**
  - **MIDPOINT OF CYLINDER - 18.02**

IMPORTANT FEATURES OF PRIMARY FRAGMENTS

- **PRODUCED BY EXPLOSION OF ONE CYLINDRICAL SOURCE**

- **DISTRIBUTED OVER A RANGE OF FRAGMENT SIZES (44)**

- **HIGH VELOCITY**
  - **GENERALLY FASTER THAN BLAST WAVE**
  - **GENERALLY FASTER THAN SECONDARY FRAGMENTS**

- **GENERATED AT 18.02* FEET ABOVE GROUND LEVEL**

*** CORRESPONDS TO MIDPOINT OF CYLINDRICAL MODEL**

REDUCTION IN PRIMARY FRAGMENT VELOCITY

- INITIAL REDUCTION OF VELOCITY OF ALL IMPACTING PRIMARY FRAGMENTS OCCURS AT MPPF HIGH BAY WALL
- ADDITIONAL REDUCTION OF VELOCITY OF SOME IMPACTING PRIMARY FRAGMENTS OCCURS AT
  - MPPF LOW BAY WALL
  - MPPF NORTH OFFICE WALL

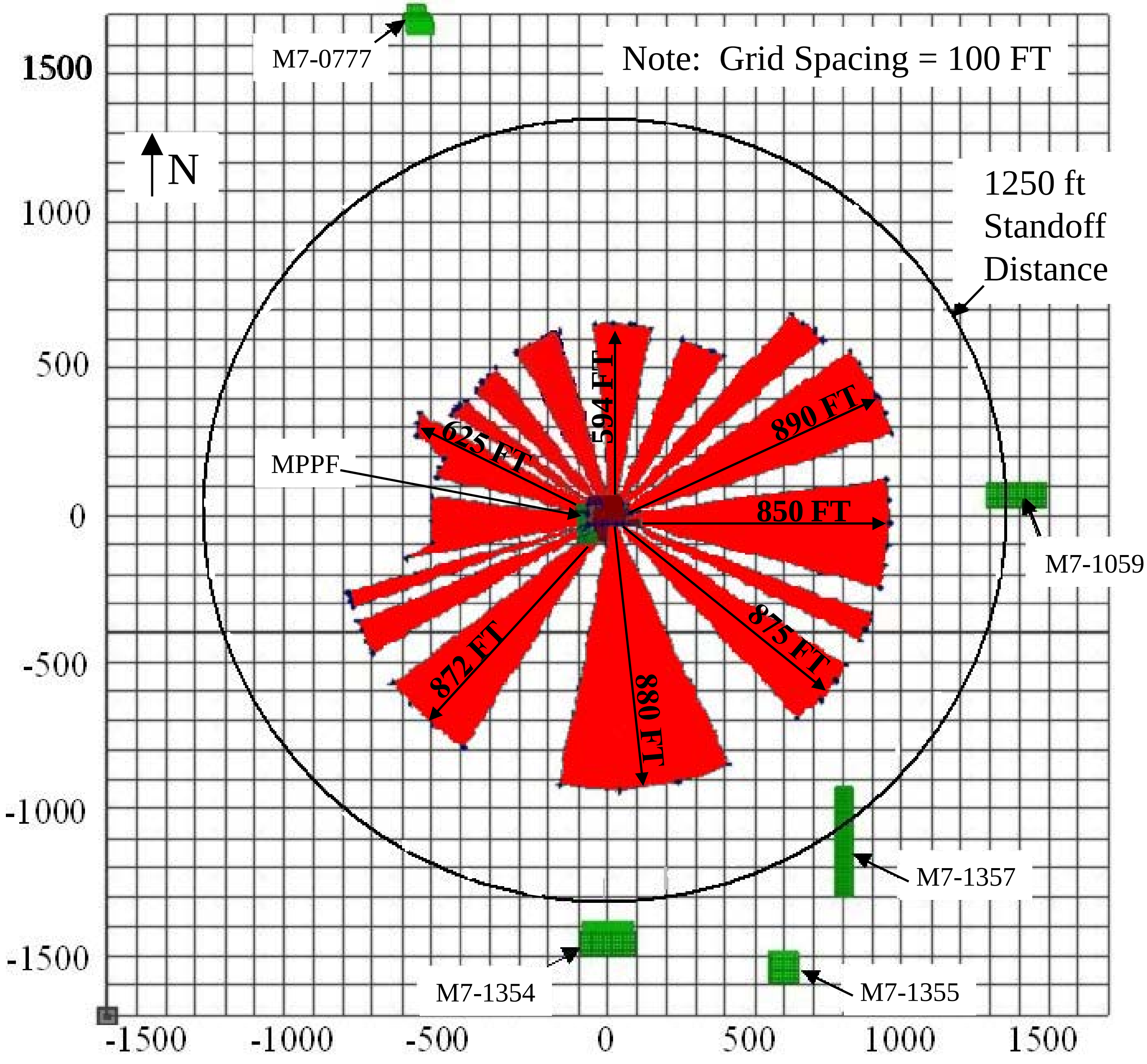

FIGURE 17. PRIMARY HAZARDOUS FRAGMENT RANGE DISTRIBUTION

CALCULATION OF MPPF SECONDARY FRAGMENTATION EFFECTS

- TECHNICAL APPROACH - BASED ON HEXFRAG SOFTWARE [14]

- RESULTS
  - SECONDARY FRAGMENT PATHS
  - FRAGMENTS IMPACTING POINTS SURROUNDING MPPF
    - MASSES
    - IMPACT VELOCITIES
    - IMPACT ENERGIES
    - NUMBER DENSITIES
  - SECONDARY HAZARDOUS FRAGMENT RANGE

SIGNIFICANT CHARACTERISTICS OF MPPF SECONDARY FRAGMENTATION

- PRIMARILY PRODUCED BY BLAST WAVE INTERACTION WITH
  - COMPONENTS OF CEV ACCESS STAND
  - COMPONENTS OF MPPF EXTERIOR WALL
- BLAST ORIGIN IS 20.91 FEET ABOVE GROUND LEVEL
- DISTRIBUTED OVER A RANGE OF FRAGMENT SIZES (10)
- LOWER VELOCITY
  - SLOWER THAN BLAST WAVE
  - SLOWER THAN PRIMARY FRAGMENTS

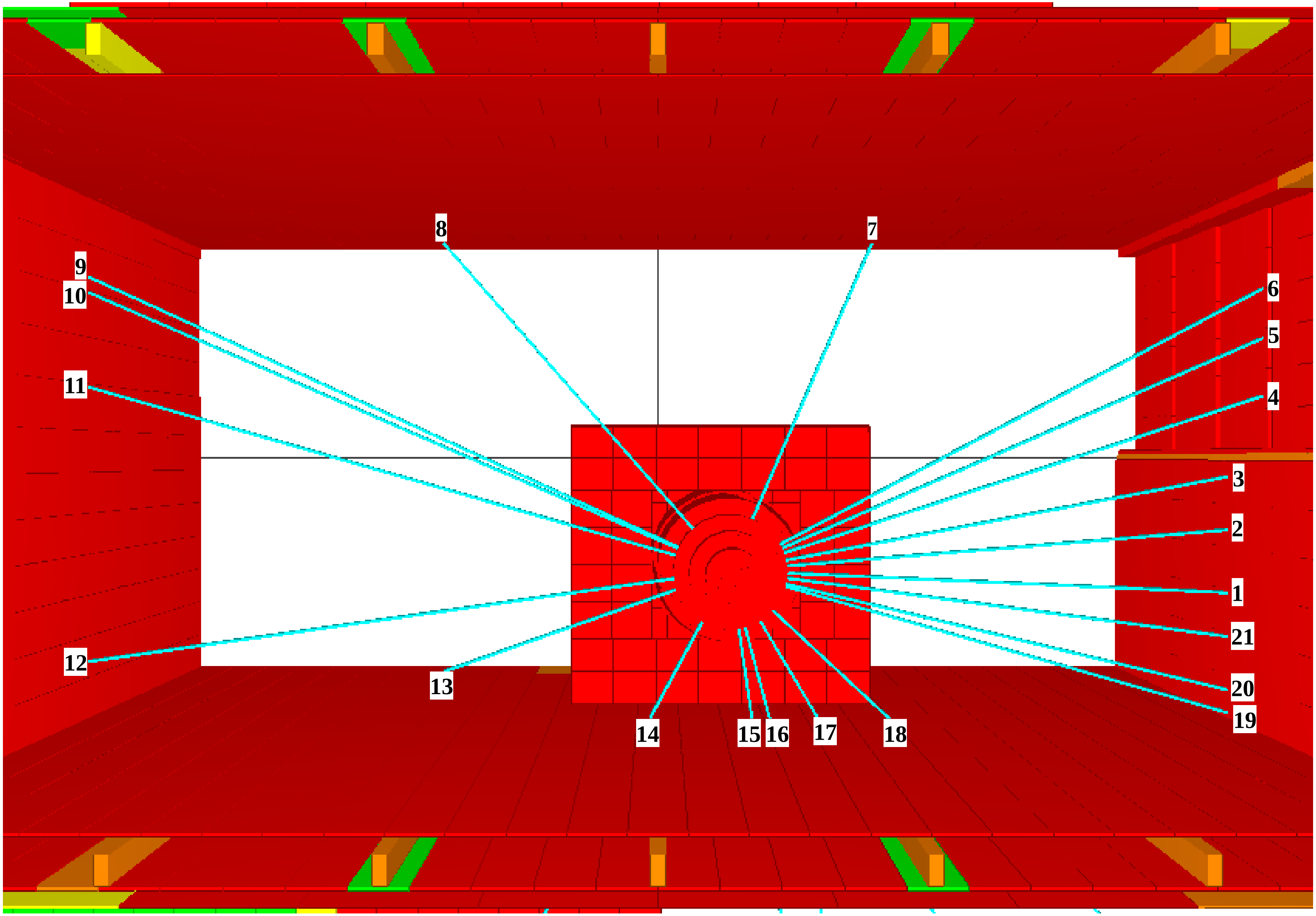

FIGURE 18. SECONDARY FRAGMENT PATHS FOR MPPF

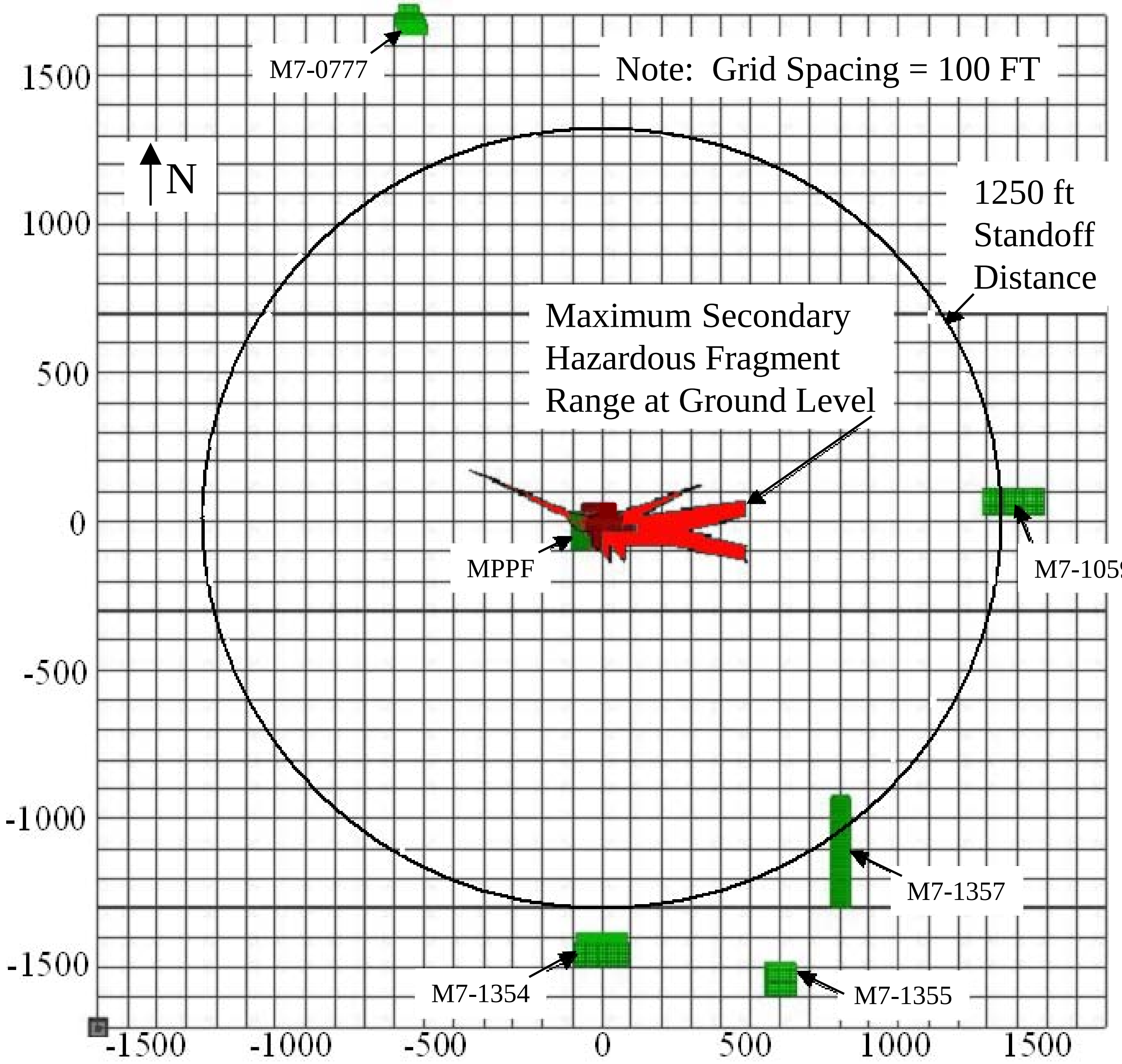

FIGURE 19. SECONDARY HAZARDOUS FRAGMENT RANGE DISTRIBUTION

SUMMARY OF ALL HAZARDS

FACILITY #/NAME	HAZARD LEVEL		
	Blast	Primary Fragmentation	Secondary Fragmentati
M7-1104/MPPF High Bay	Severe	Severe	Severe
M7-1104/MPPF North Office	Slight-to-Severe	Severe	Moderate-to-Severe
M7-1104/MPPF Low Bay	Slight-to-Severe	Severe	Moderate-to-Severe
M7-1104/MPPF Flight Data Control Room	Slight-to-Severe	Severe	Moderate-to-Severe
M7-1104/MPPF Annex	Slight-to-Severe	Severe	Moderate-to-Severe
M7-1357/Multi Operations Support Bldg (MOSB)	None-to-Slight	None-to-Slight	None
M7-1354/Payload Hazardous Servicing Facility (PHSF) Building	None-to-Slight	None-to-Slight	None
M7-1355/PHSF Storage Bay	None-to-Slight	None-to-Slight	None
M7-1059/Hypergolic Maintenance Facility	None-to-Slight	None-to-Slight	None
M7-0777/Canister Rotation Facility - High Bay	None-to-Slight	None-to-Slight	None
M7-0777/Canister Rotation Facility - Office Area	None	None-to-Slight	None

CONCLUSIONS

- BLAST HAZARDS
  - LIMITED PRIMARILY TO MPPF COMPONENTS
  - 0.9 PSI CONTOUR EXTENDS OUT TO NO MORE THAN 436 FT BEYOND MPPF PERIMETER
  - 1.2 PSI CONTOUR EXTENDS OUT TO NO MORE THAN 355 FT BEYOND MPPF PERIMETER

- PRIMARY FRAGMENT HAZARDS
  - REPRESENT GREATEST CONCERN OUTSIDE MPPF
  - EXTEND OUT TO 898 FT BEYOND MPPF PERIMETER

- SECONDARY FRAGMENT HAZARDS EXTEND OUT NO MORE THAN 420 FT BEYOND MPPF PERIMETER